NASA/TM–2014-218177

Identification of Vehicle Health Assurance Related Trends

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March 2014

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1. INTRODUCTION

1.1. Purpose of Study

The goal of the Vehicle Systems Safety Technology (VSST) Project of the NASA's Aviation Safety Program (AvSP) is to "enable a reduction in accidents and incidents through enhanced vehicle design, structure, systems, and operating concepts" (Ref. 1). The VSST has three technical challenges contributing to this goal:

TC1: Improve Crew Decision-Making and Response in Complex Situations (CDM)

TC2: Maintain Vehicle Safety between Major Inspections (MVS)

TC3: Assure Safe and Effective Aircraft Control under Hazardous Conditions (ASC)

The VSST management team uses systems analysis (1) "to provide independent information regarding the projected impact of the VSST research portfolio on its aviation safety goals"; and (2) "to identify key issues and maintain a research portfolio leading to potential solutions to the three challenges" (Ref. 1). To assist the management in achieving these objectives, several systems analysis milestones have been specified in the VSST project plan. The systems analysis milestone for fiscal year (FY) 2014 is focused on the MVS Technical Challenge. The goal of MVS is to "develop and demonstrate new integrated health management and failure prevention technologies to assure the integrity of vehicle systems between major inspection intervals and maintain vehicle state awareness during flight" (Ref. 1). The expected research outcome of the MVS TC is the set of six research products listed in Table 1.

Table 1. MVS List of Research Products

MAINTAIN VEHICLE SAFETY BETWEEN MAJOR INSPECTION (MVS)		
MVS-1.1	**Hybrid Structural Damage Diagnosis**	Assessment of airframe structural health via sensors coupled with rapid large area inspection methods.
MVS-1.2	**Integrated Sensing and Healing System (ISHS)**	Integration of self-healing materials that enable early detection of damage precursors, and increase durability and damage tolerance of airframes.
MVS-2.1	**Vehicle Integrated Propulsion Research (VIPR)**	Technologies developed under this element diagnose and monitor propulsion system in real-time, and mitigate potential issues through easily integrated, small, and low weight sensors avoiding costly retrofits while maintaining safety.
MVS-2.2	**Mitigating Turbomachinery Structural Failure**	This technology will enable advanced inspection methods for recently implemented engine material technologies as well as robust engine material design methods for future emerging technologies.
MVS-3.1	**Vehicle-Level Diagnostics and Integration**	Integration of diagnostic data to provide an overall assessment of the vehicle state to identify potential maintenance and safety issues between inspections.
MVS-3.2	**Physics-Based Models and Algorithms for Wiring Fault Detection**	Combination of physics-based model and probabilistic fault detection algorithm to diagnose and identify chafed wires and degraded connectors for electrical wiring and interconnect systems (EWIS).

As detailed in the VSST project plan (Ref. 1), the MVS TC is described as follows:

"MVS research centers around preventing vehicle failures, as well as quickly detecting and containing them when they do occur. MVS addresses critical risks for maintaining vehicle safety. The greatest amount of information about an airplane's current health is currently obtained during major inspections. These inspections are thorough, costly, and are performed at set intervals based on fleet-wide averages for system and component reliability. There is a generous safety margin built into these intervals, but there are occasions where problems can come up during operations that were undetected at the last major inspection. MVS works to provide information on potential safety-related systems problems to support in-flight decision-making and targeted maintenance that can address these problems. It accomplishes this goal through integrated systems consisting of high-capability sensors and diagnostic algorithms. It also develops capabilities to help preclude some of the most critical failures that can arise."

A summary of the goals, objectives, and products for the MVS TC are graphically depicted using an objectives tree format (Ref. 2) in Figure 1.

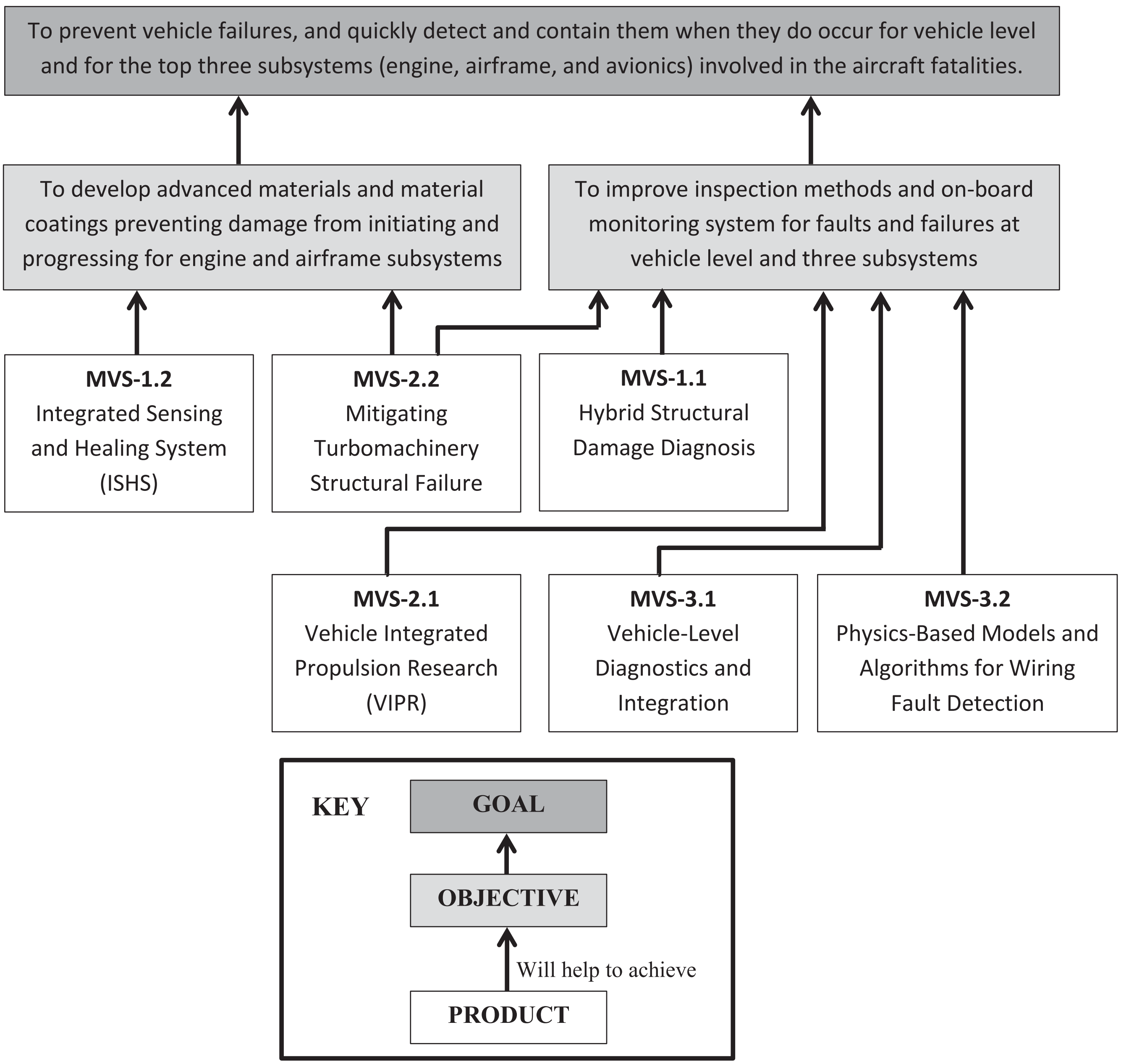


Figure 1. MVS Objectives Tree

The specific MVS related FY14 systems analysis milestone is stated below:

1) Deliver analysis of trends in aviation as related to vehicle health management (VHM) by reviewing the most current statistical and prognostics data available about accidents and incidents related to VHM areas.
2) Deliver assessment of future directions in aviation technology related to VHM research areas through review of literature from academia, industry and other government agencies to establish requirements for future work in VHM.

1.2. Overview of Study Contents

The outcomes of this study are addressed in the next sections and in sequential order. Outcome 1 is given in Section 2, which contains a summary of statistical analyses of accident and incident data that has been conducted by NASA researchers. Outcome 2 is addressed in Section 3, which is a summary of vehicle health assurance issues and future research needs that were derived from literature reviews, databases, and aviation subject-matter experts. Finally, Section 4 discusses and concludes the study.

2. SUMMARY OF NASA STATISTICAL STUDIES

Systems analysis personnel within the NASA AvSP have recently conducted statistical analyses of accident and incident data that are related to the MVS Technical Challenge. This section summarizes the results of these analyses.

2.1. Analysis of NTSB/FAA Data

A recent study has been conducted using accident data from the National Transportation Safety Board (NTSB) Aviation Accident and Incident Data System (restricted to 1996-2010), and incident data from the Federal Aviation Administration (FAA) Accident/Incident Data System (restricted to 1996-2010), especially those related to system/component failures/malfunctions (SCFM).

The information the NTSB investigators collect during their investigations of these aviation events resides in the NTSB Aviation Accident and Incident Data System. A copy of this database in Microsoft Access format was obtained from the Aviation Safety Information Analysis and Sharing (ASIAS) department of the FAA’s Office of Aviation Safety in June 2012. At that point in time, the NTSB investigation was not complete for a substantial number of 2011 accidents, particularly those which occurred toward the end of the year. For this reason, all work on the database was restricted to 1986-2010, which was primarily an update of two years beyond the previous working version of the data the systems analysis personnel maintain. The update process requires several months of cross-checking various data elements and attempting to fill in any missing data, followed by the assignment of occurrence categories to each accident.

The NTSB database includes events involving a wide variety of aircraft (airplanes, helicopters, hot air balloons, gliders, ultralight, etc.) with operations conducted under various Federal Aviation Regulations (Part 91: General Aviation, Part 121: Commercial Air Carriers, Part 129: Foreign Air Carriers, Part 135: Commuters and On-Demand Air Taxis, Part 137: Agricultural Operations, etc.). The NTSB considers each event to be either an accident or an incident, with their definitions defined in Ref. 3. The NTSB does not investigate all incidents, but incidents as well as accidents are reported to the FAA by pilots, airport personnel and private citizens.

The FAA maintains a database with the information that they receive in these reports and collect in their investigations. A copy of the FAA's Accident/Incident Data System (AIDS) was obtained from Aviation Safety Information Analysis and Sharing (ASIAS) in July of 2011, which was late enough in the year that nearly all incidents from 2010 had been investigated. The current working copy of the AIDS database includes incidents from 1985-2010. A recent separate analysis showed substantial differences in several accident characteristics in the data prior to 1996. As such, for this analysis the decision was made to select the most recently available fifteen years' worth of data (1996-2010).

In 2008, the FAA revised the amount of data recorded for each incident, making the database even less informative. Some of the data fields are now blank for the most recent incidents. One of those fields was previously used to determine which of the Part 135 flights were scheduled and which were non-scheduled. As a result, it is not possible to present incident data separately for scheduled versus non-scheduled Part 135 operations among incidents later than 2007. For most of this report, the Part 135 incident data are restricted to 1996-2007 and all data from 2008-2010 are ignored.

In order to describe the types of aircraft which were involved in these accidents and incidents, the specific aircraft make and model (and in many cases, aircraft series) was determined for each accident and nearly all incidents. For the vast majority of events, this information could be easily found in the data record. For some events it was necessary to consult the FAA's aircraft registry database.

All aircraft in the data system for the chosen time period (1996-2010) were divided into groups based on some combination of engine type, aircraft use, aircraft size, and aircraft complexity. The aircraft categories are as follows:

- Jet engine
    - Wide Body Jet Airliners
    - Narrow Body Jet Airliners
    - Regional Jets
    - Medium Sized Business Jets
    - Small Business Jets (maximum takeoff weight <= 12,500 lbs)
- Turbo-prop engine
    - Large Turbo-props (maximum takeoff weight >= 32,000 lbs and more than 30 seats)
    - Medium Turbo-props (12,500< maximum takeoff weight <32,000 lbs or 15-30 seats)
    - Small Turbo-props (maximum takeoff weight <12,500 lbs and less than 15 seats)
- Reciprocating engine
    - Heavier multiple reciprocating engines (maximum takeoff weight >15,000 lbs)
    - Lighter multiple reciprocating engines (maximum takeoff weight < 15,000 lbs)
    - Single reciprocating engine, retractable landing gear
    - Single reciprocating engine, fixed landing gear
    - Light Sport Aircraft

The systems involved in the failures and malfunctions are presented separately in Section 2.1.1 for four categories of flight operations (Part 121, Scheduled Part 135, Non-Scheduled Part 135, and Part 91). A separate analysis looks at SCFM in different categories of aircraft type in Section 2.1.2.

2.1.1. System/Component Failures/Malfunctions by Operation Category

This section examines system/component failure/malfunction (SCFM) by flight operations. A summary of the SCFM events can be found in Table 2. The incident data for Part 135 are from 1996-2007 only. Across all operation categories, between 15 and 22 percent of accidents (row "Accidents with SCFM") during 1996-2010 involved a failure or malfunction of some aircraft system or component. The lowest proportion of accidents and fatal accidents associated with SCFM was in Part 91 (12-15%, column "Part 91"), while the lowest percentage of fatalities was in Scheduled Part 135 (9%). Among Part 121 flights, SCFM accounted for 16 percent of all accidents, 36 percent of fatal accidents, and 66 percent of all fatalities. In Part 135 flights, SCFM accounted for 19 to 22 percent of all accidents, 18 to 19 percent of fatal accidents, and 9 to 19 percent of all fatalities. Between 36 and 62 percent of all incidents included SCFM across all operation categories; the lowest percentage again was within Part 91.

Table 2. Summary of System/Component Failure/Malfunction Accidents and Incidents by Operation Category

Type of Event	Part 121	Part 135—Scheduled	Part 135—Non-Scheduled	Part 91
Total Accidents	619	108	768	17,628
Accidents with SCFM	97 (15.7%)	20 (18.5%)	167 (21.7%)	2,581 (14.6%)
Fatal Accidents	36	16	173	3,260
Fatal SCFM Accidents out of all Fatal Accidents	13 (36.1%)	3 (18.8%)	31 (17.9%)	387 (11.9%)
Total Fatalities	1,190	94	427	6,295
Fatalities in accidents with SCFM	782 (65.7%)	8 (8.5%)	81 (19.0%)	811 (12.9%)
Total Incidents	4,890	295	1,343	17,411
Incidents with SCFM	3008 (61.5%)	180 (61.0%)	759 (56.5%)	6323 (36.3%)

For each accident and incident, the system affected by the malfunction or failure was determined (see Table 3). In some events multiple systems were affected, and in these cases the first system affected was selected. For example, if an electrical malfunction preceded an engine fire, that event was categorized under “Electrical”. Engine and landing gear failures/malfunctions combined (highlighted rows) for between 56 and 69 percent of all SCFM accidents, and between 48 and 79 percent of all SCFM incidents. No other single system accounted for more than fifteen percent of the failure/malfunction accidents or incidents.

Table 3. Initial System Affected by Failure or Malfunction in Accidents and Incidents, by Operation Category (with tall poles highlighted)

System	Part 121	Part 135—Scheduled	Part 135—Non-Scheduled	Part 91
Total SCFM Accidents	97	20	167	2581
Electrical	8 (8.2%)	1 (5.0%)	7 (4.2%)	110 (4.3%)
Engine	28 (28.9%)	7 (35.0%)	60 (35.9%)	1,133 (43.9%)
Flight Controls	7 (7.2%)	1 (5.0%)	8 (4.8%)	144 (5.6%)
Fuel	1 (1.0%)	1 (5.0%)	12 (7.2%)	226 (8.8%)
Hydraulic	9 (9.3%)	1 (5.0%)	10 (6.0%)	63 (2.4%)
Instrumentation/ Communication/Navigation	2 (2.1%)	1 (5.0%)	0 (0.0%)	28 (1.1%)
Landing Gear	26 (26.8%)	6 (30.0%)	54 (32.3%)	635 (24.6%)
Structure	6 (6.2%)	0 (0.0%)	9 (5.4%)	185 (7.2%)
Other	10 (10.3%)	2 (10.0%)	5 (3.0%)	36 (1.4%)
Unknown	0 (0.0%)	0 (0.0%)	2 (1.2%)	20 (0.8%)
Total SCFM Incidents	3,008	180	759	6,323
Electrical	133 (4.4%)	8 (4.4%)	36 (4.7%)	479 (7.6%)
Engine	834 (27.7%)	48 (26.7%)	211 (27.8%)	1,729 (27.3%)
Flight Controls	309 (10.3%)	11 (6.1%)	14 (1.8%)	124 (2.0%)
Fuel	103 (3.4%)	6 (3.3%)	29 (3.8%)	249 (3.9%)
Hydraulic	234 (7.8%)	11 (6.1%)	30 (4.0%)	160 (2.5%)
Instrumentation/ Communication/Navigation	45 (1.5%)	2 (1.1%)	5 (0.7%)	44 (0.7%)
Landing Gear	612 (20.3%)	64 (35.6%)	352 (46.4%)	3,288 (52.0%)
Structure	128 (4.3%)	13 (7.2%)	37 (4.9%)	114 (1.8%)
Other	610 (20.3%)	17 (9.4%)	45 (5.9%)	136 (2.2%)

For the purpose of further examination, the systems were divided into four groups (engine or fuel system, flight controls or structure, landing gear or hydraulics, and everything else). In the majority of accidents and incidents involving flight control failures or malfunctions, the issue was with the control surface itself, or with a cable leading to the control surface, rather than with the switch, selector or computer which controlled the movement of the surface; thus, it seemed reasonable to group these with other structural (mostly wing) failures. Similarly, most cases of hydraulic failure led to the inoperability of the landing gear or brakes, providing a natural link between those two systems.

Table 4. Event Characteristics by Failure/Malfunction System Group and by Operation Category

System Group	Event Characteristics	Part 121	Part 135—Scheduled	Part 135—Non-Scheduled	Part 91
Engine or Fuel System	Total Accidents	29	8	72	1359
	Fatal Accidents	4 (13.8%)	1 (12.5%)	14 (19.4%)	180 (13.2%)
	Total Fatalities	42	2	41	354
	Aircraft Destroyed	3 (10.3%)	1 (12.5%)	15 (20.8%)	213 (15.7%)
Flight Controls or Structure	Total Accidents	13	1	17	329
	Fatal Accidents	5 (38.5%)	0	10 (58.8%)	163 (49.5%)
	Total Fatalities	397	0	24	358
	Aircraft Destroyed	5 (38.5%)	0	8 (47.1%)	141 (42.9%)
Landing Gear or Hydraulic	Total Accidents	35	7	64	698
	Fatal Accidents	0	1 (14.3%)	1 (1.6%)	1 (0.1%)
	Total Fatalities	0	5	4	2
	Aircraft Destroyed	0	1 (14.3%)	2 (3.1%)	11 (1.6%)
Instrumentation, Communication, Navigation, Electrical, Other, Unknown	Total Accidents	20	4	14	195
	Fatal Accidents	4 (20.0%)	1 (25.0%)	6 (42.9%)	43 (22.1%)
	Total Fatalities	343	1	12	97
	Aircraft Destroyed	6 (30.0%)	1 (25.0%)	5 (35.7%)	62 (31.8%)

Table 4 shows the number of accidents, the number of fatal accidents, the total number of fatalities, and the proportion of aircraft destruction in each group of the accidents. Flight control/structural failures/malfunctions accounted for less than fifteen percent of SCFM accidents (from Table 3) but were the most deadly of the four groups (between 39 and 59 percent of fatal accidents from Table 4), and in general the most likely to result in aircraft destruction (between 39 and 47 percent of aircraft destroyed). Landing gear/hydraulic malfunctions were very rarely fatal, regardless of flight operation, and rarely resulted in aircraft destruction. Fatalities and aircraft destruction associated with engine/fuel system malfunctions were more likely than with landing gear/hydraulic failures, but less likely than either of the other two groups.

Figures 2-5 compare the number of accidents for each group of initially affected systems across three time periods. Among Part 121 accidents (Figure 2), flight control/structural malfunctions occurred the least in every time period, but decreased less over time than the other categories.

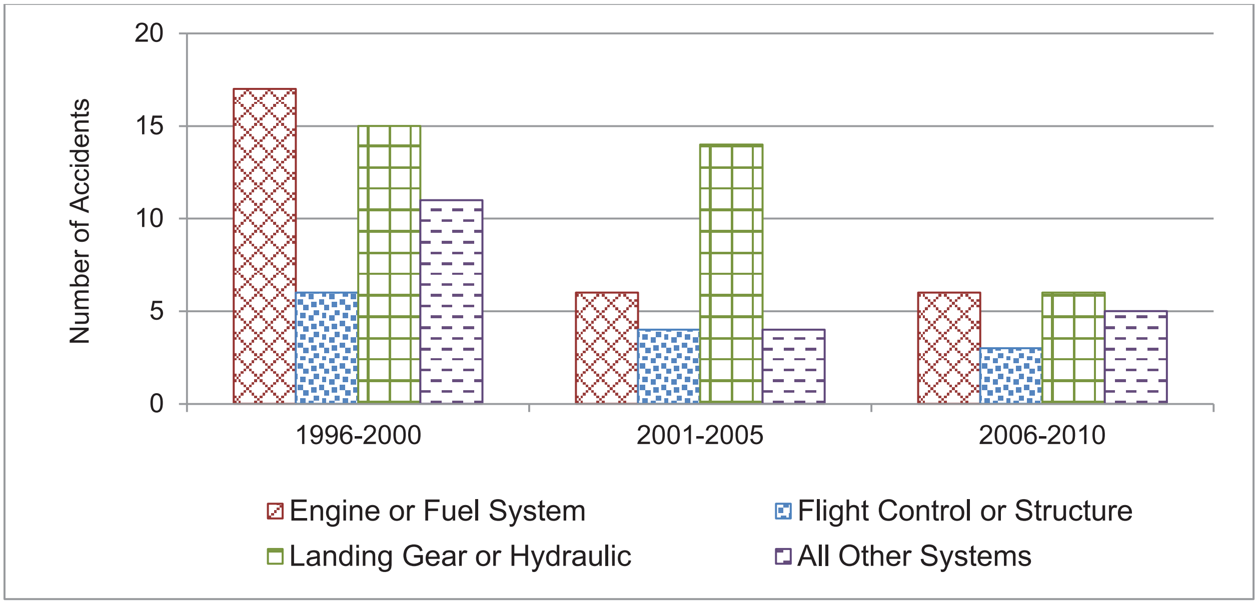


Figure 2. Number of Accidents in Groups of Initially Affected Systems Across Three Time Periods for Part 121.

Among Scheduled Part 135 accidents (Figure 3), only one accident included a flight control/structural malfunction (a jammed control yoke), and the number of engine/fuel system failures/malfunctions did not decrease over time. Among Non-Scheduled Part 135 accidents (Figure 4), the number of engine/fuel system malfunctions decreased substantially over time, and the number of flight control/structural malfunctions decreased slightly. In Part 91 (Figure 5), the number of flight control/structural malfunctions, and also the number of landing gear/hydraulic malfunctions, has remained nearly constant, while the number of engine/fuel system malfunctions has declined.

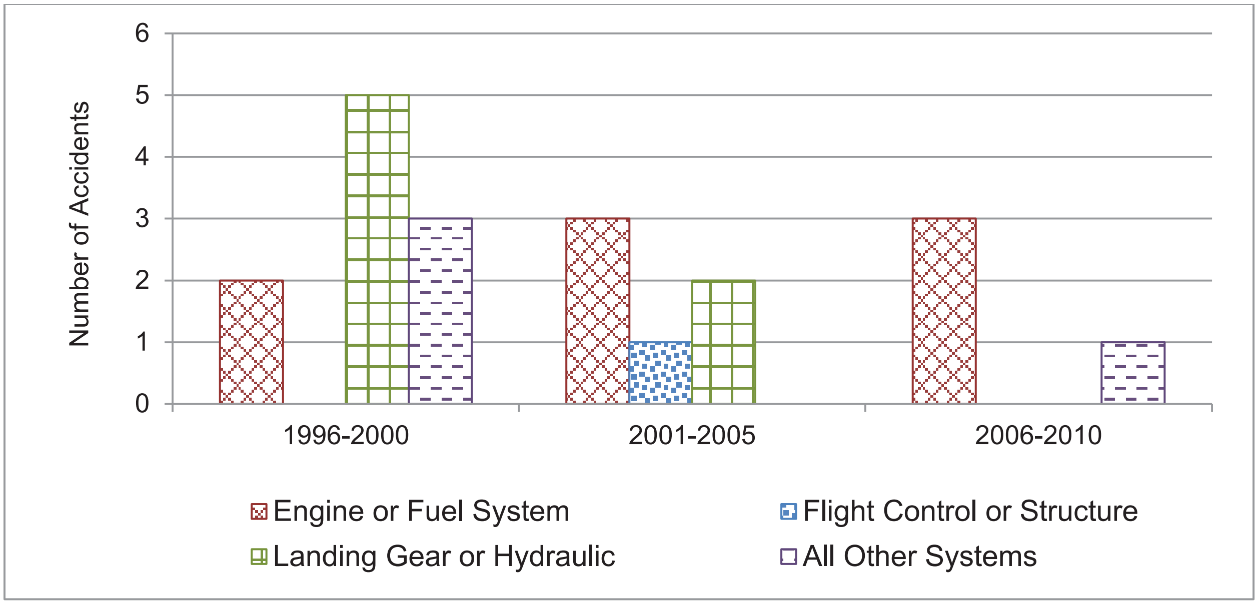


Figure 3. Number of Accidents in Groups of Initially Affected Systems Across Three Time Periods for Scheduled Part 135.

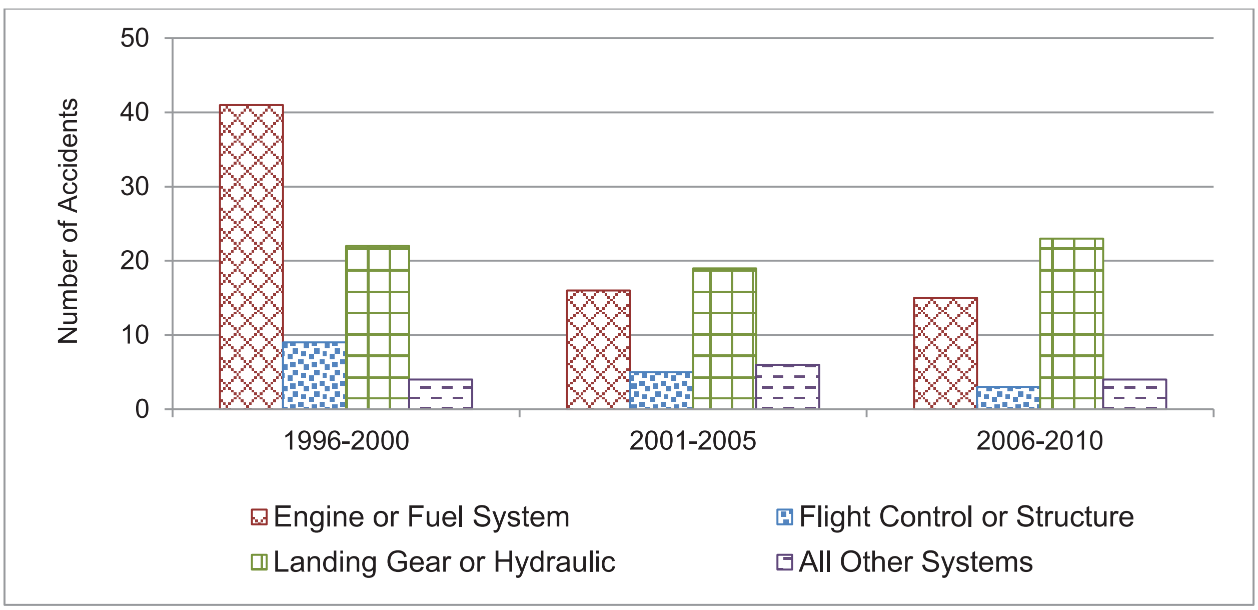


Figure 4. Number of Accidents in Groups of Initially Affected Systems Across Three Time Periods for Non-Scheduled Part 135.

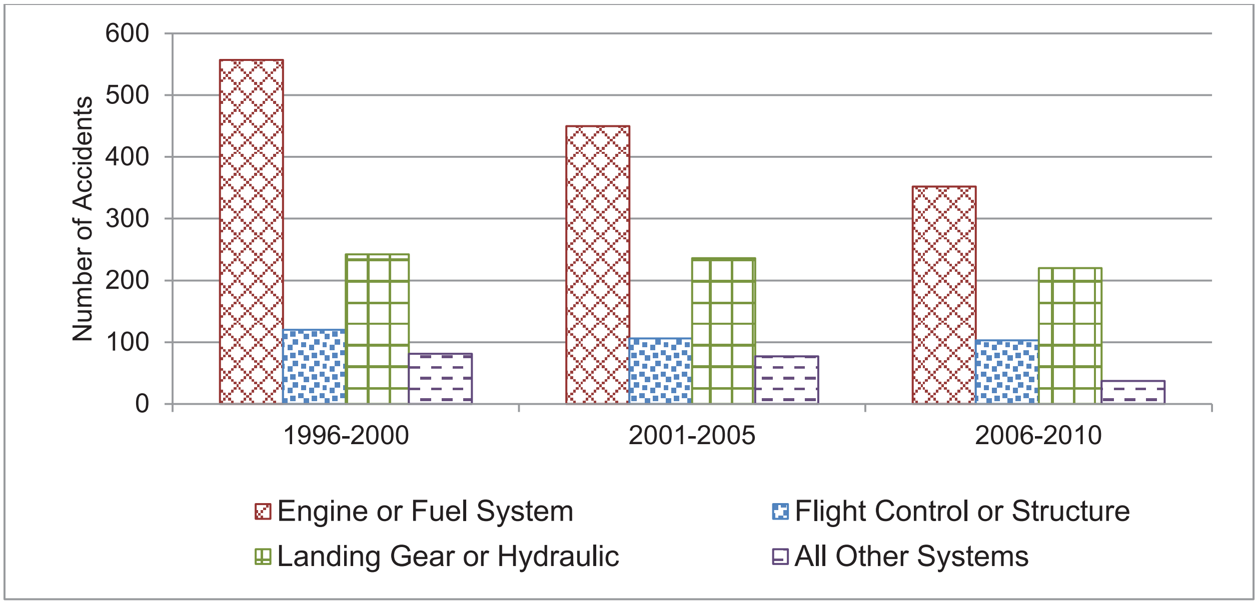


Figure 5. Number of Accidents in Groups of Initially Affected Systems Across Three Time Periods for Part 91.

Figures 6-9 compare the number of incidents in each of the four groups of initially affected systems across three time periods. Among Part 121 and Part 135 incidents (Figures 6, 7, and 8), malfunctions in all four groups have decreased over time. In Part 91 (Figure 9), the number of flight control/structural malfunctions has been consistently low, and the incidence of all other malfunctions and failures has declined.

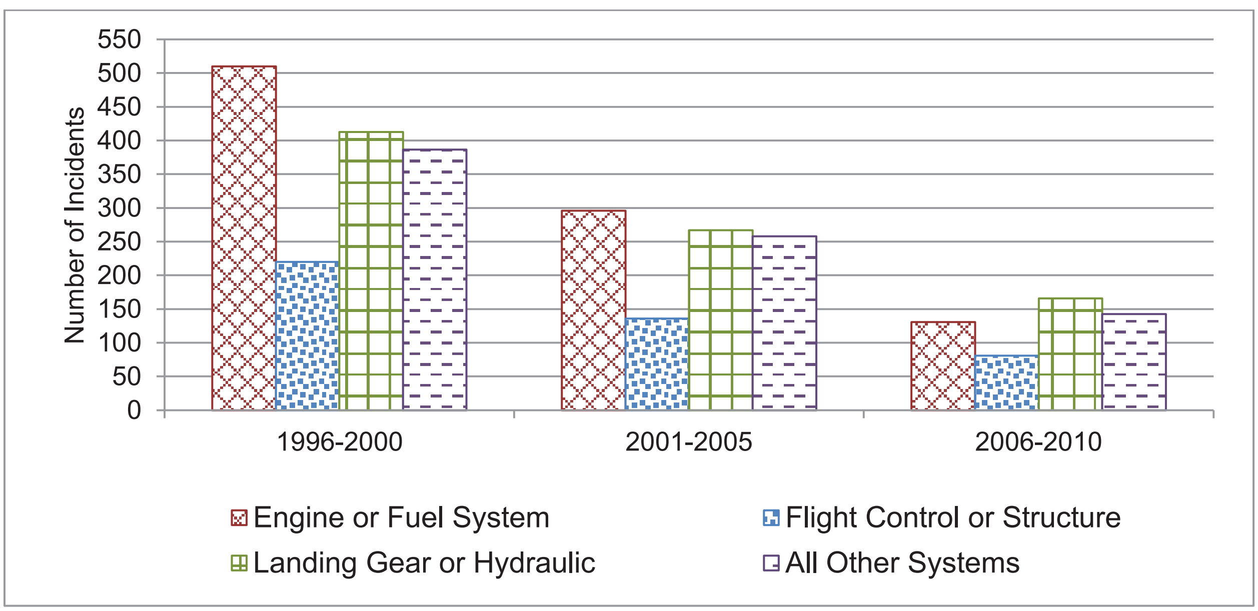


Figure 6. Number of Incidents in Groups of Initially Affected Systems Across Three Time Periods for Part 121.

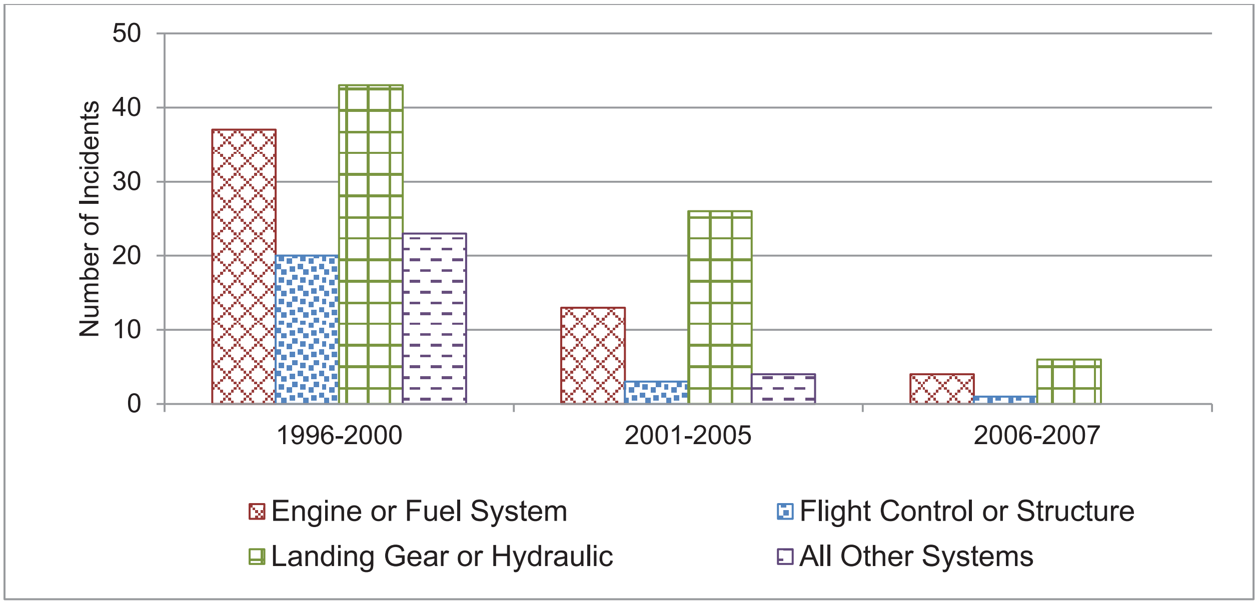


Figure 7. Number of Incidents in Groups of Initially Affected Systems Across Three Time Periods for Scheduled Part 135.

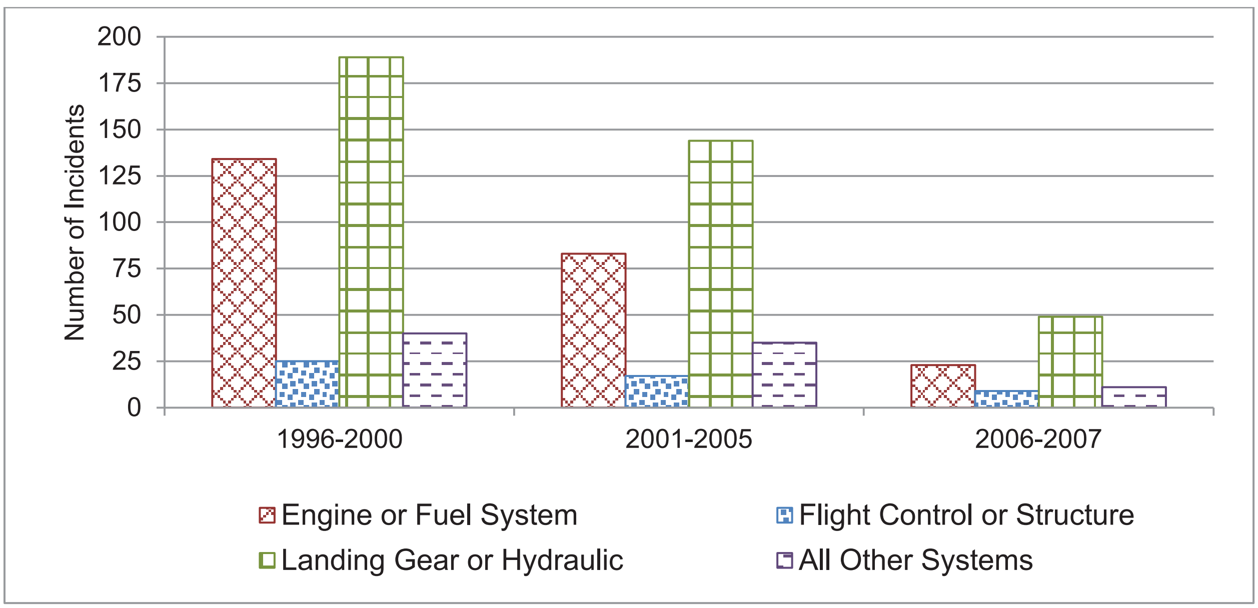


Figure 8. Number of Incidents in Groups of Initially Affected Systems Across Three Time Periods for Non-Scheduled Part 135.

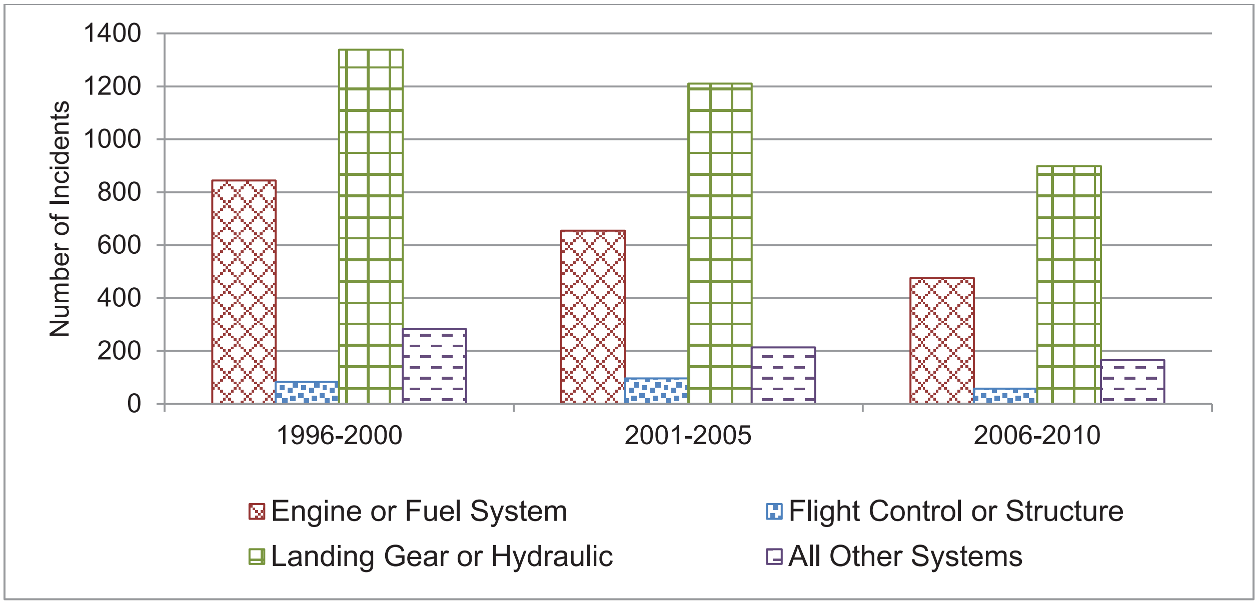


Figure 9. Number of Incidents in Groups of Initially Affected Systems Across Three Time Periods for Part 91.

2.1.2. System/Component Failures/Malfunctions by Aircraft Category

This section examines SCFM within aircraft engine types, rather than flight operation. A full breakdown analysis of aircraft categories based on some combination of engine type, aircraft use, aircraft size, and aircraft complexity involved in the 1996-2010 accidents and incidents can be found in Ref. 3. The data were grouped in this section as follows:

1. Jet Engine Aircraft
2. Turbo-Prop Engine Aircraft
3. Reciprocating Engine Aircraft
    - Multiple Reciprocating Engine
    - Single Reciprocating Engine

Figure 10 shows accident volumes of engine types by operation category. Jet aircraft were involved in 81 percent of Part 121 accidents. In contrast, 87 percent of Part 91 accidents involved aircraft with a single reciprocating engine, with 9 percent of the aircraft having multiple reciprocating engines and the remaining 4 percent spread out over the other 2 engine types. Scheduled Part 135 accidents occurred on basically three engine types, none of them jets: turbo-props (30%), multiple reciprocating engines (30%) and single reciprocating engines (41%). Non-Scheduled Part 135 accidents predominantly involved aircraft with reciprocating engines, either single (40%) or multiple (31%), although nearly eight percent of the accident aircraft were jets and 21 percent had turbo-prop engines.

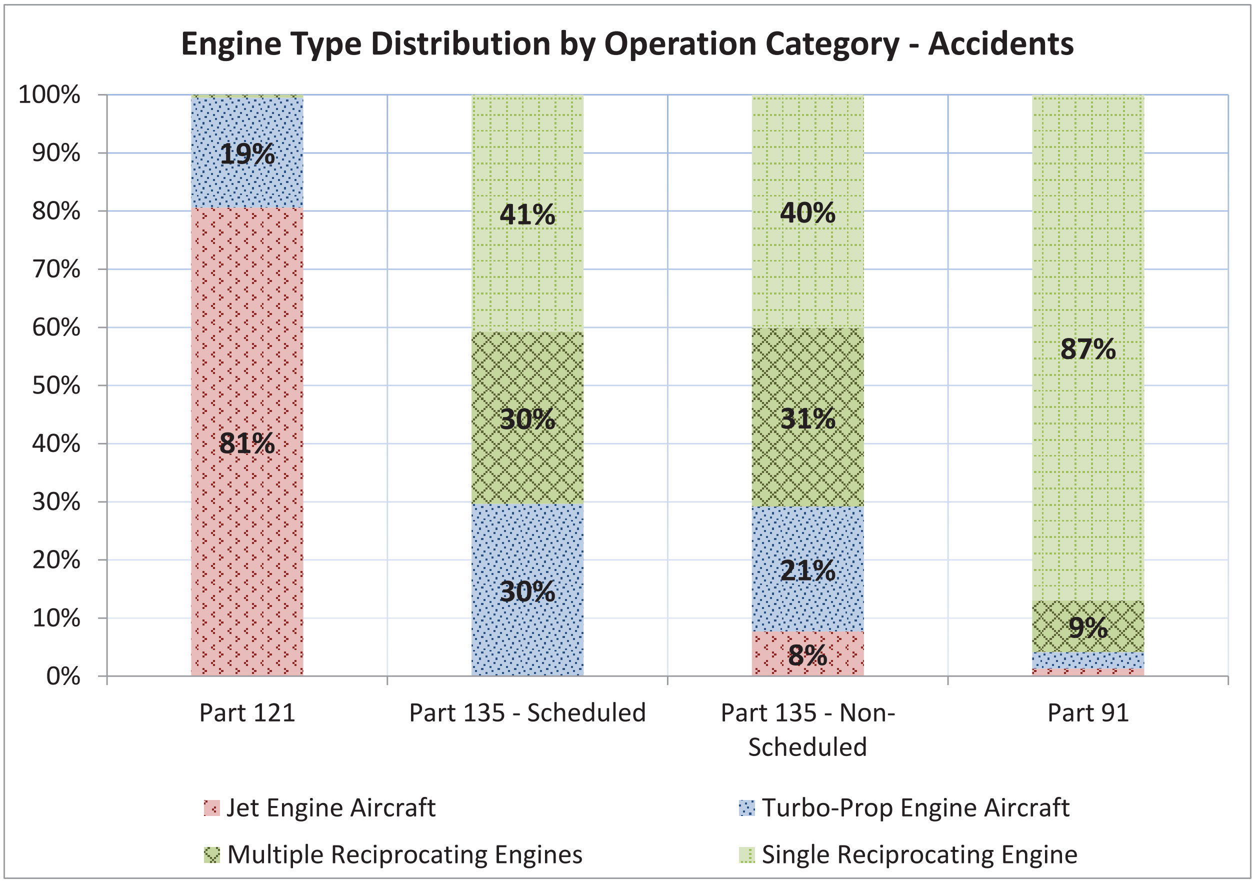


Figure 10. Summary of Engine Type in Accidents by Operation Category.

A similar summary of the engine types involved in the incidents can be found in Figure 11. Seventy-three percent of Part 121 incidents occurred on flights with jet aircraft. In contrast, aircraft with reciprocating engine were involved in 91 percent of Part 91 incidents and 57 percent of Non-Scheduled Part 135 incidents. Twenty-three percent of Non-Scheduled Part 135 incidents occurred on flights with turbo-prop engines, and another 19 percent occurred in jet aircraft. Fifty-one percent of Scheduled Part 135 incidents occurred on turbo-props, and another 45 percent in aircraft with reciprocating engines.

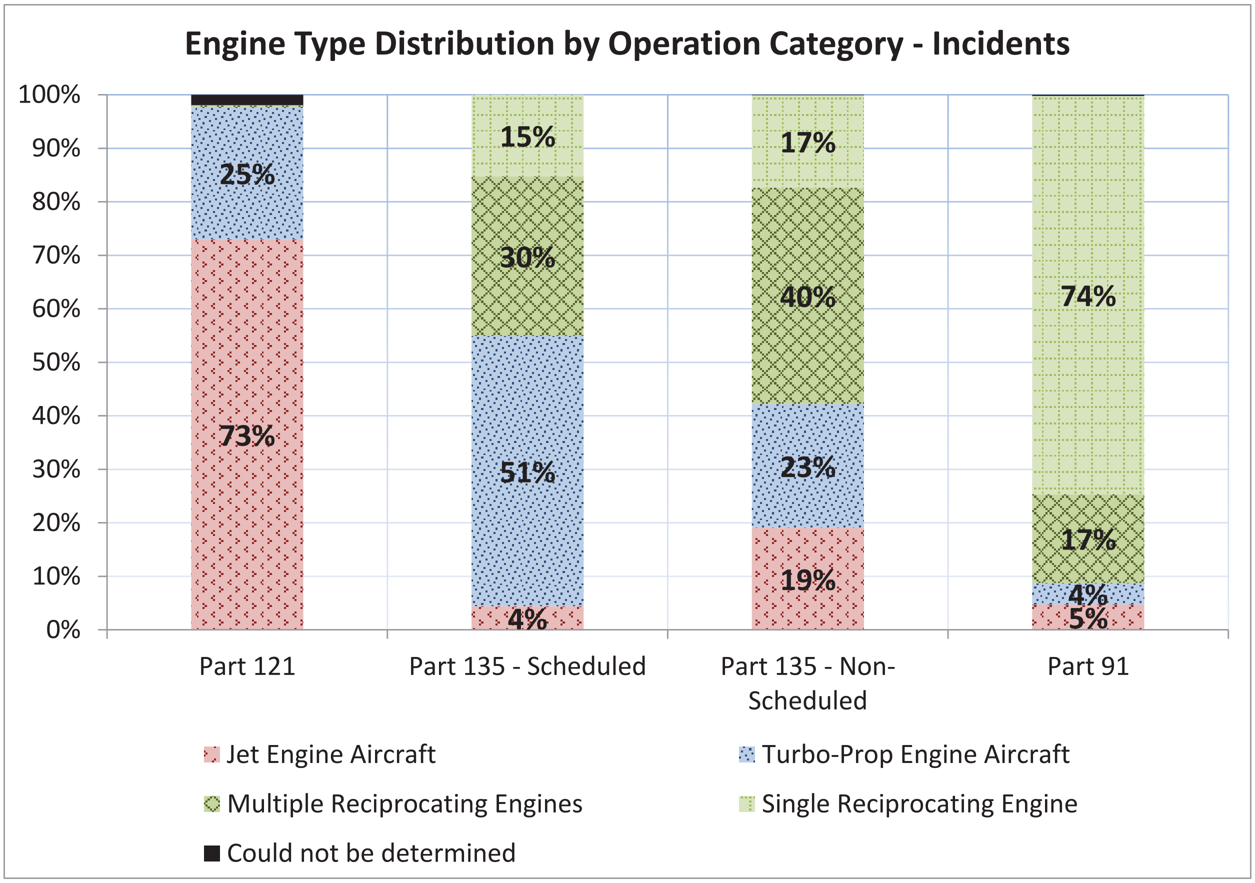


Figure 11. Summary of Engine Type in Incidents by Operation Category.

Table 5 summarizes the accident and incident data within the above engine types regardless of flight operation categories. Eighteen percent of jet and turbo-prop accidents (row "Accidents with SCFM") included a system/component failure/malfunction. The highest proportions of fatal accidents and fatalities were in jets (20% in fatal accidents, and 54% in fatalities). In contrast, the lowest percentages of fatal accidents and fatalities were in single-engine aircraft (12% and 13%, respectively).

Ninety percent of the reciprocating engine aircraft involved in accidents had a single engine (15,685/17,523); however, single engine accidents involving SCFM occurred less frequently (14%) than SCFM accidents with multiple engine aircraft (22%).

Twenty-two percent of multiple-engine (reciprocating) aircraft accidents involved SCFM; this was the highest percentage among all engine types (row "Accidents with SCFM"). Interestingly, the lowest percentage was associated with single-engine aircraft (14 percent). Among incidents (row "Incidents with SCFM"), however, 58 to 61 percent of jet, turbo-prop, and multiple-engine (reciprocating) aircraft incidents involved SCFM, compared with 31 percent for single-engine incidents.

Table 5. Summary of System/Component Failure/Malfunction Accidents and Incidents by Engine type

Type of Event	Jet Engines	Turbo-Prop Engines	Multiple Reciprocating Engines	Single Reciprocating Engines	All Reciprocating Engines
Total Accidents	786	814	1,838	15,685	17,523
Accidents with SCFM	142 (18%)	149 (18%)	409 (22%)	2,165 (14%)	2,574 (15%)
Fatal Accidents	85	240	590	2,570	3,160
Fatal SCFM Accidents out of all Fatal Accidents	17 (20%)	32 (13%)	88 (15%)	297 (12%)	385 (12%)
Total Fatalities	1,416	767	1,267	4,556	5,823
Fatalities in accidents with SCFM	767 (54%)	126 (16%)	208 (16%)	581 (13%)	789 (14%)
Total Incidents	4,722	2,437	3,624	13,270	16,894
Incidents with SCFM	2,741 (58%)	1,484 (61%)	2,088 (58%)	4,073 (31%)	6,161 (36%)

Table 6 shows the first system involved in a failure or malfunction for the accidents and incidents, broken down by engine type. Engine and landing gear failures/malfunctions combined for between 56 and 69 percent of all SCFM accidents, and between 49 and 84 percent of all SCFM incidents. No other single system accounted for more than fifteen percent of the failure/malfunction accidents or incidents. There were no fuel system malfunctions among accidents in jet aircraft during 1996-2010.

Table 6. Initial System Affected by Failure or Malfunction in Accidents and Incidents, by Engine type (with tall poles highlighted**)**

System	Jet Engines	Turbo-Prop Engines	Multiple Reciprocating Engines	Single Reciprocating Engines	All Reciprocating Engines
Total SCFM Accidents	142	149	409	2,165	2,574
Electrical	12 (8%)	4 (3%)	16 (4%)	94 (4%)	110 (4%)
Engine	26 (18%)	51 (34%)	113 (28%)	1,038 (48%)	1,151 (45%)
Flight Controls	13 (9%)	10 (7%)	19 (5%)	118 (5%)	137 (5%)
Fuel	0 (0%)	8 (5%)	28 (7%)	204 (9%)	232 (9%)
Hydraulic	17 (12%)	8 (5%)	12 (3%)	46 (2%)	58 (2%)
Instrumentation/ Communication/ Navigation	3 (2%)	3 (2%)	8 (2%)	17 (1%)	25 (1%)
Landing Gear	54 (38%)	46 (31%)	167 (41%)	454 (21%)	621 (24%)
Structure	5 (4%)	13 (9%)	34 (8%)	148 (7%)	182 (7%)
Other	11 (8%)	6 (4%)	7 (2%)	30 (1%)	37 (1%)
Unknown	1 (1%)	0 (0%)	5 (1%)	16 (1%)	21 (1%)
Total SCFM Incidents	2,741	1,484	2,088	4,073	6,161
Electrical	122 (4%)	59 (4%)	109 (5%)	369 (9%)	478 (8%)
Engine	703 (26%)	403 (27%)	367 (18%)	1,369 (34%)	1,736 (28%)
Flight Controls	276 (10%)	87 (6%)	29 (1%)	69 (2%)	98 (2%)
Fuel	92 (3%)	46 (3%)	46 (2%)	204 (5%)	250 (4%)
Hydraulic	205 (7%)	97 (7%)	78 (4%)	63 (2%)	141 (2%)
Instrumentation/ Communication/ Navigation	32 (1%)	28 (2%)	5 (0%)	30 (1%)	35 (1%)
Landing Gear	633 (23%)	461 (31%)	1,390 (67%)	1,893 (46%)	3,283 (53%)
Structure	126 (5%)	100 (7%)	39 (2%)	35 (1%)	74 (1%)
Other	552 (20%)	203 (14%)	25 (1%)	41 (1%)	66 (1%)

As before, the systems were divided into four groups (engine or fuel system, flight controls or structure, landing gear or hydraulics, and everything else). Table 7 shows various characteristics of accidents in these four groups, by aircraft groups determined by the type of engine. Among jet aircraft, the most frequently affected systems are landing gear or hydraulic, whereas engine or fuel system malfunctions are by far most frequent among aircraft with reciprocating engines (row "Total Accidents"). In turbo-props, these two groups are similar. Regardless of engine type, flight controls or structural malfunctions are most likely, and landing gear or hydraulic failures least likely, to lead to fatal injuries and aircraft destruction (rows "Fatal Accidents" and "Aircraft Destroyed").

Table 7. Event Characteristics by Failure/Malfunction System Group and by Engine Type

System Group	Event Characteristics	Jet Engines	Turbo-Prop Engines	Reciprocating Engines
Engine or Fuel System	Total Accidents	26	59	1383
	Fatal Accidents	4 (15.4%)	10 (16.9%)	185 (13.4%)
	Total Fatalities	45	29	365
	Aircraft Destroyed	3 (11.5%)	15 (25.4%)	214 (15.5%)
Flight Controls or Structure	Total Accidents	18	23	319
	Fatal Accidents	6 (33.3%)	14 (60.9%)	158 (49.5%)
	Total Fatalities	367	69	343
	Aircraft Destroyed	6 (33.3%)	13 (56.5%)	135 (42.3%)
Landing Gear or Hydraulic	Total Accidents	71	54	679
	Fatal Accidents	1 (1.4%)	1 (1.9%)	1 (0.1%)
	Total Fatalities	4	5	2
	Aircraft Destroyed	1 (1.4%)	1 (1.9%)	12 (1.8%)
Instrumentation, Communication, Navigation, Electrical, Other, Unknown	Total Accidents	27	13	193
	Fatal Accidents	6 (22.2%)	7 (53.8%)	41 (21.2%)
	Total Fatalities	351	23	79
	Aircraft Destroyed	8 (29.6%)	5 (38.5%)	61 (31.6%)

Figures 12-15 compare the number of accidents in these four system groups across three time periods by engine type. Figures 16-19 similarly compare the number of incidents. Among jet aircraft (Figure 12), the number of landing gear/hydraulic malfunctions decreased over time, but remained the most frequent type of malfunction. The other three system groups did not change substantially, but all were least frequent during 2001-2005.

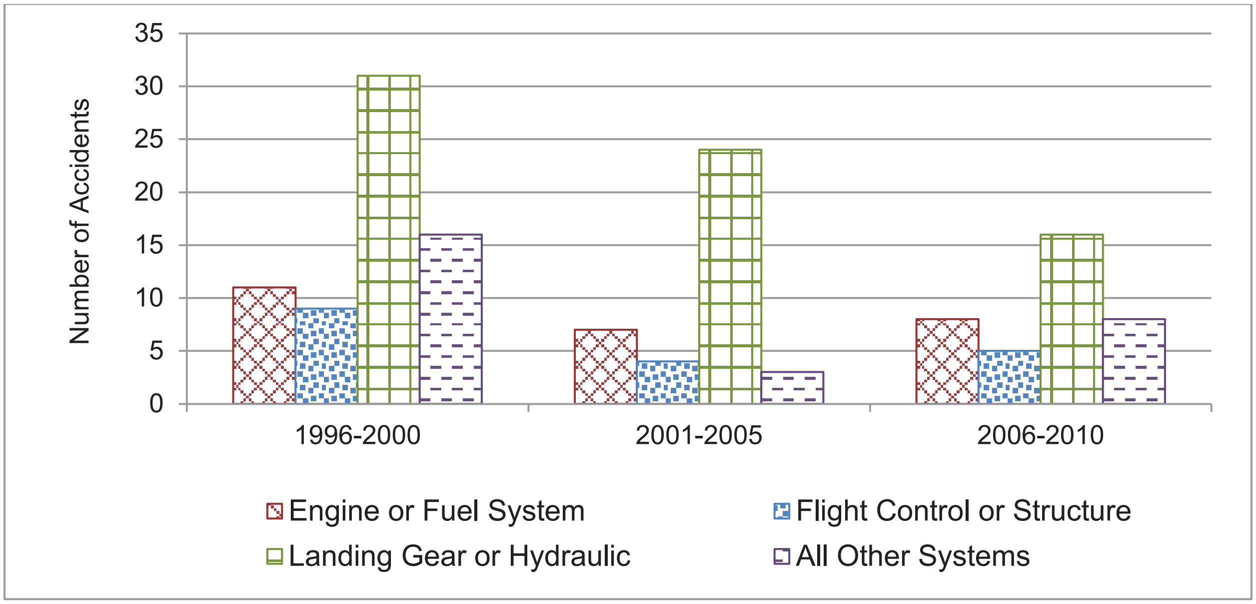


Figure 12. Number of Accidents in Groups of Initially Affected Systems Across Three Time Periods for Jet Aircraft.

Among turbo-prop aircraft (Figure 13), flight controls/structural malfunctions have increased, while engine/fuel and landing gear/hydraulic malfunctions have decreased.

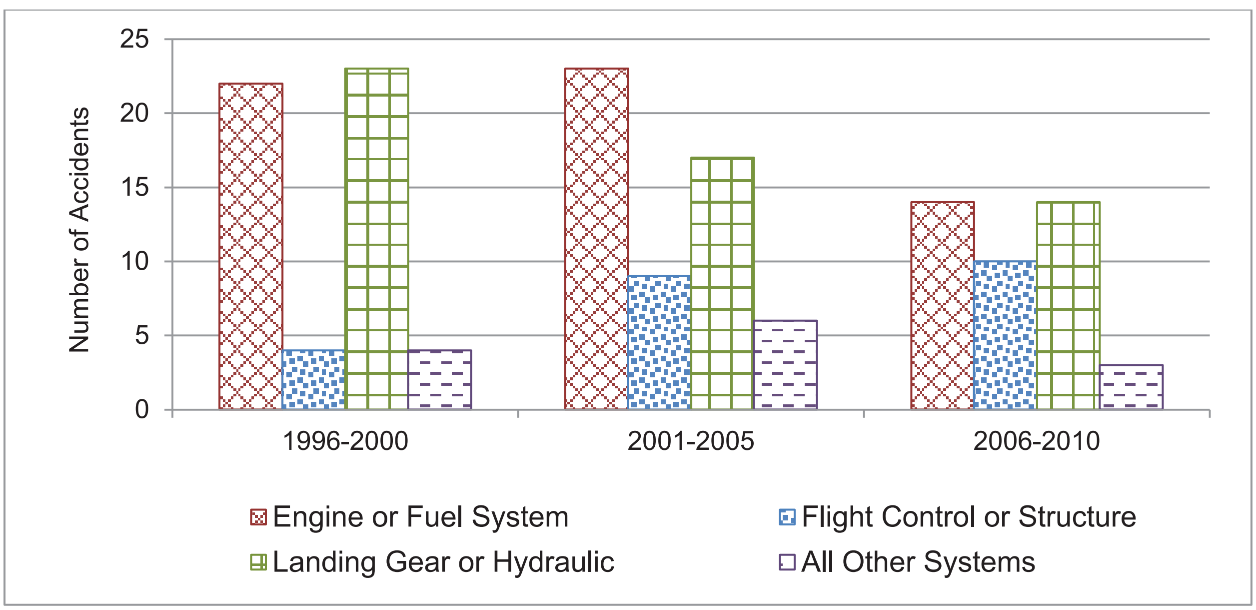


Figure 13. Number of Accidents in Groups of Initially Affected Systems Across Three Time Periods for Turbo-Prop Aircraft.

Among multiple reciprocating engine aircraft (Figure 14), landing gear/hydraulic malfunctions have increased, while engine/fuel malfunctions have decreased. The number of flight controls/structural malfunctions has not changed much.

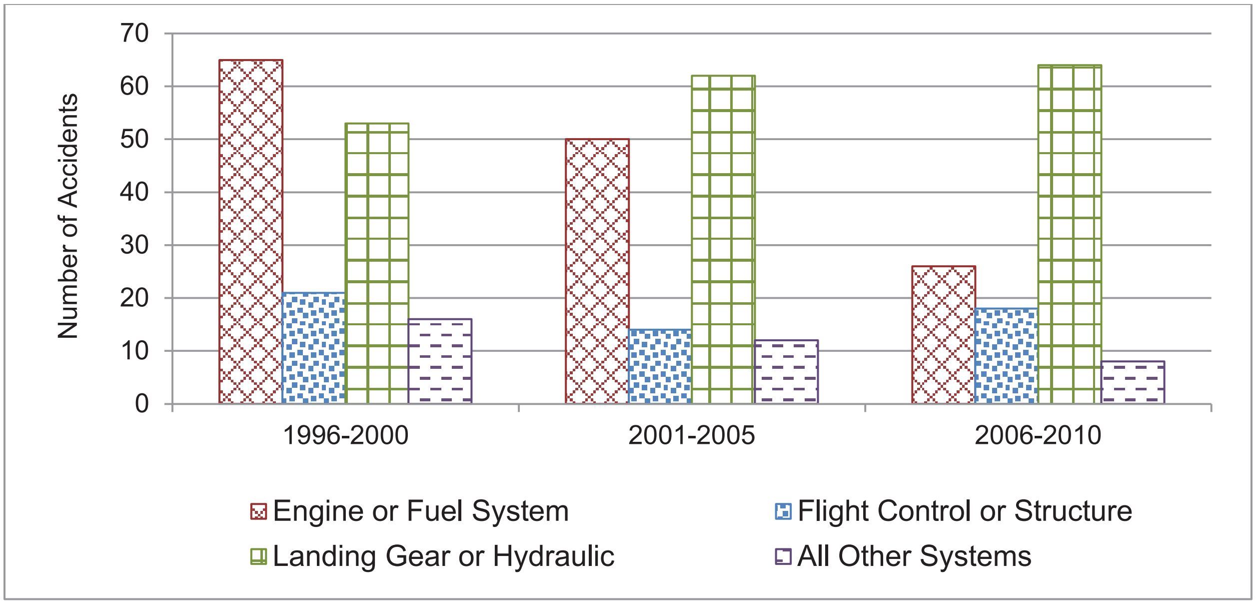


Figure 14. Number of Accidents in Groups of Initially Affected Systems Across Three Time Periods for Multiple Reciprocating Engine Aircraft.

Among single reciprocating engine aircraft (Figure 15), engine/fuel malfunctions have decreased substantially, while all other types of malfunctions have decreased only slightly.

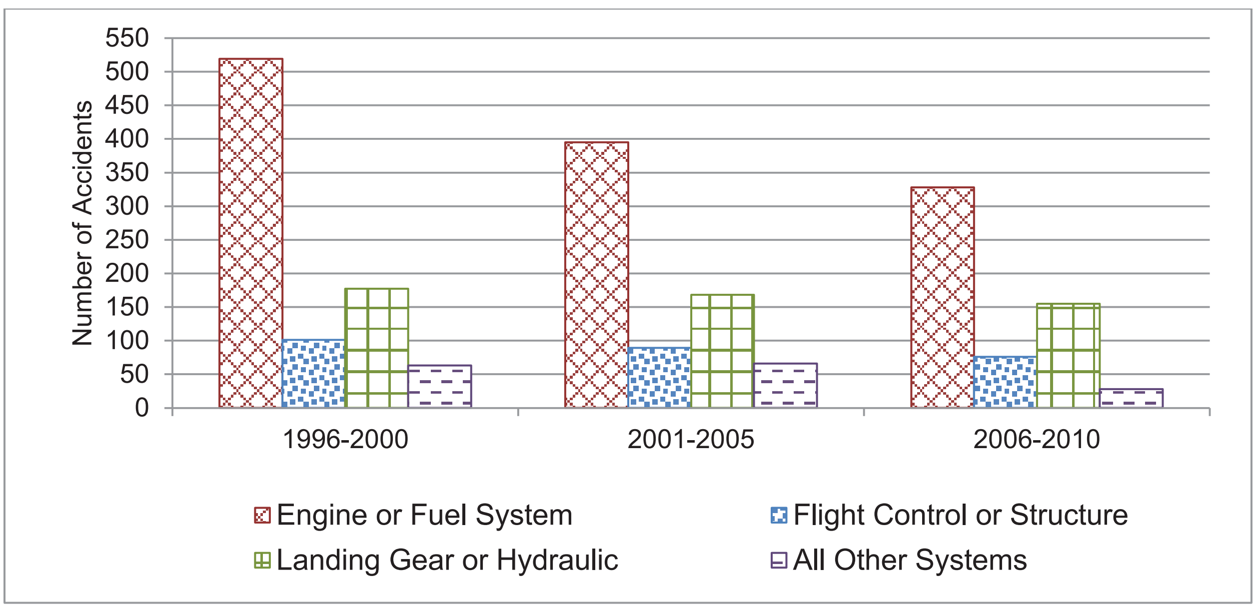


Figure 15. Number of Accidents in Groups of Initially Affected Systems Across Three Time Periods for Single Reciprocating Engine Aircraft.

The number of incidents in all four system groups decreased over time for all engine types (Figures 16-19). The general trend was that within each time period, the descending order by frequency was landing gear/hydraulic, engine/fuel, other, and flight controls/structural. An exception to this general trend was for jet aircraft during 1996-2000, where engine/fuel malfunctions were the most frequent.

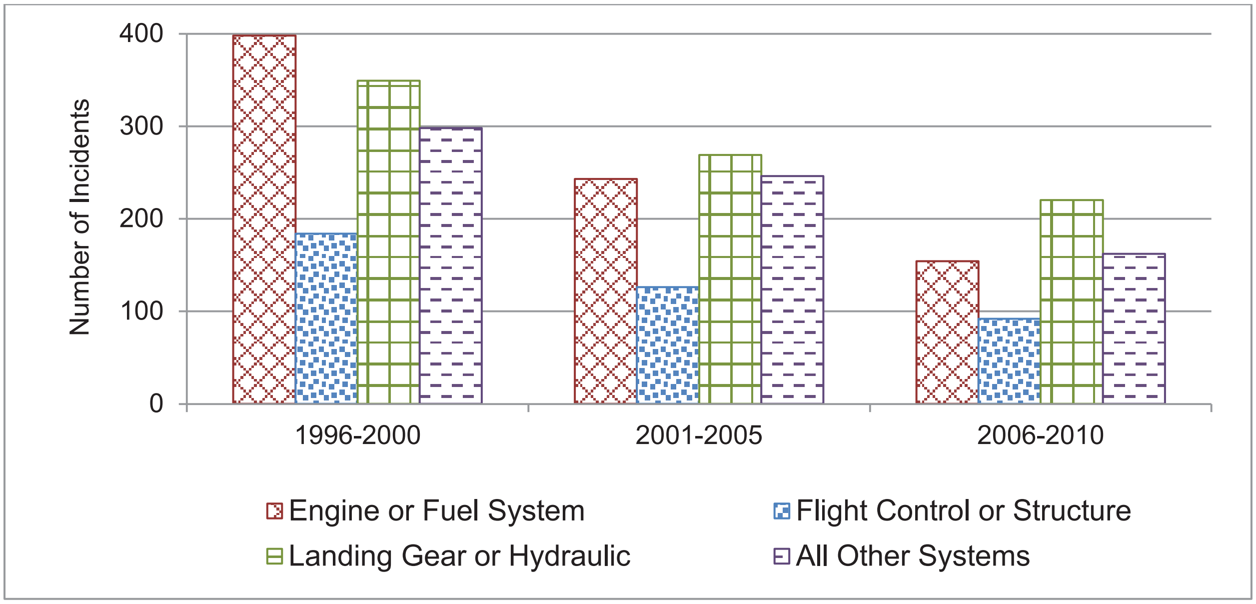


Figure 16. Number of Incidents in Groups of Initially Affected Systems Across Three Time Periods for Jet Aircraft.

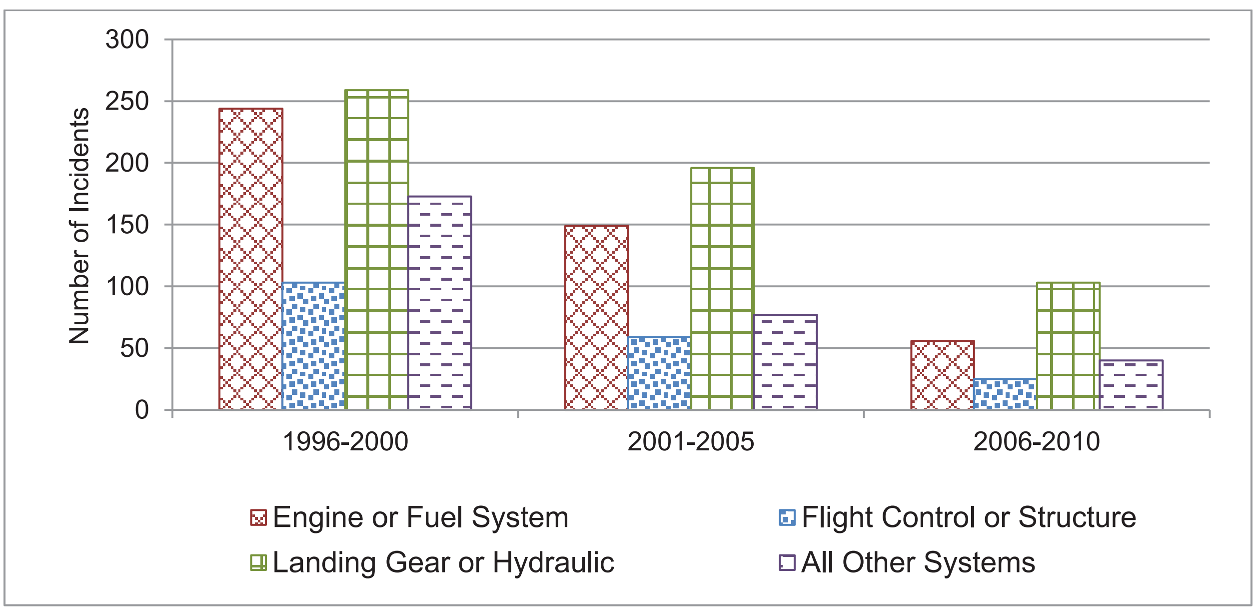


Figure 17. Number of Incidents in Groups of Initially Affected Systems Across Three Time Periods for Turbo-Prop Aircraft.

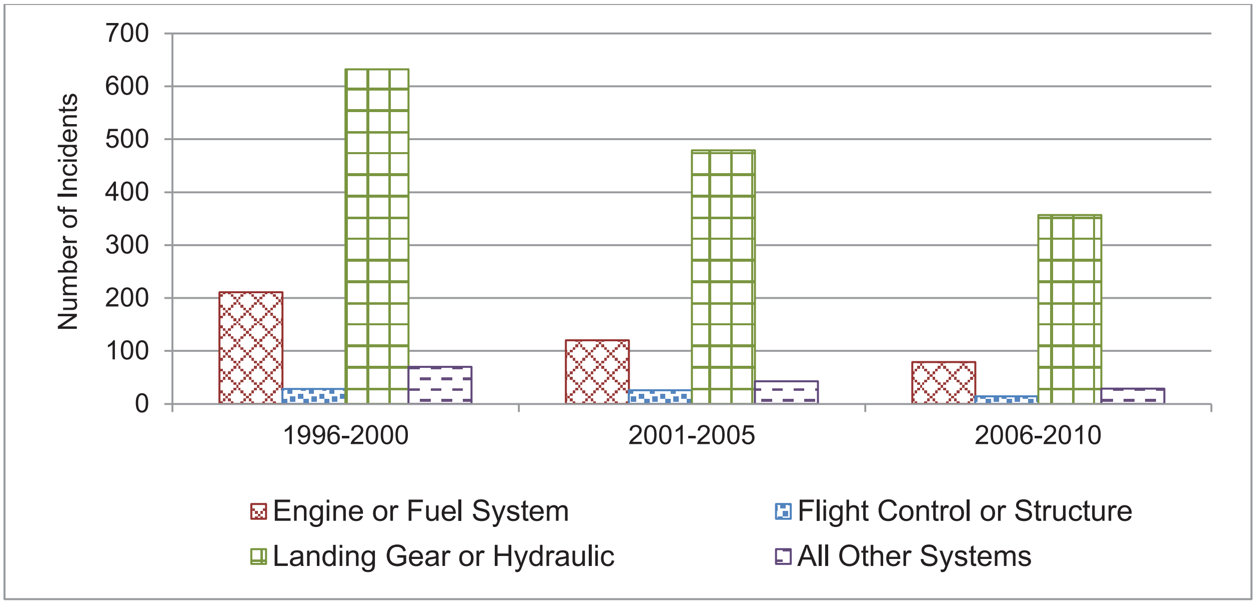


Figure 18. Number of Incidents in Groups of Initially Affected Systems Across Three Time Periods for Twin Reciprocating Engine Aircraft.

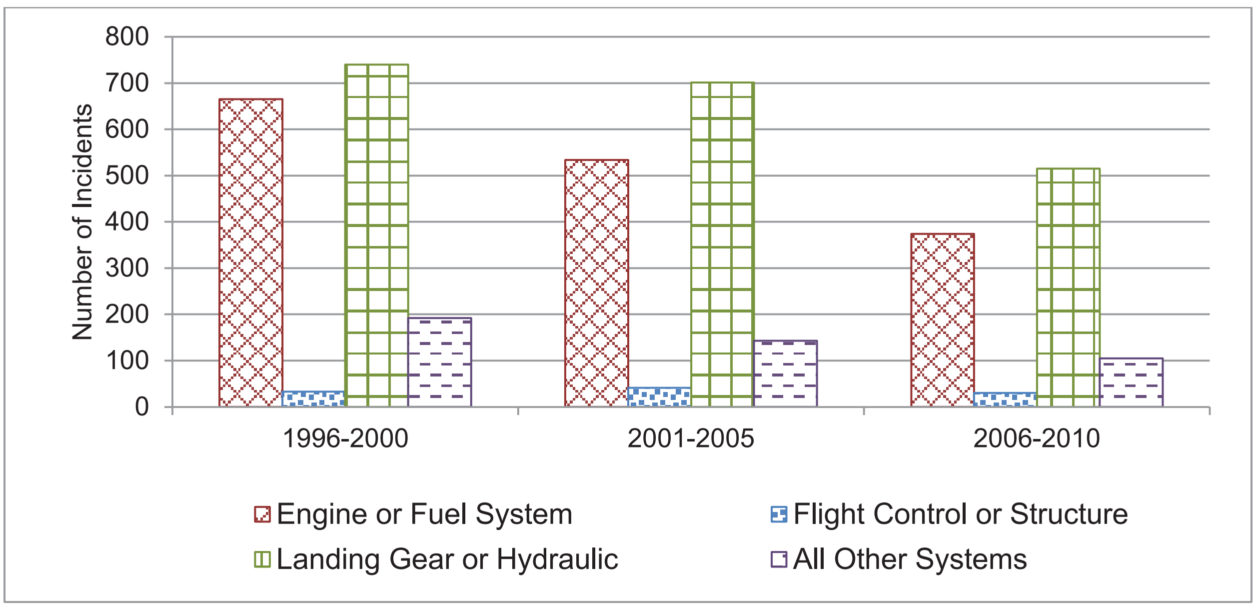


Figure 19. Number of Incidents in Groups of Initially Affected Systems Across Three Time Periods for Single Reciprocating Engine Aircraft.

2.2. Analysis of ASRS Data

AvSP systems analysis personnel have recently conducted a study of the NASA Aviation Safety Reporting System (ASRS) incident data. The incidents in the ASRS are reported voluntarily, and are subject to self-reporting biases. These incidents are not verified by the Federal Aviation Administration (FAA) or the National Transportation Safety Board (NTSB). Voluntary incident reports cannot be considered a representative sample of the underlying population of events they describe (Ref. 4). As such, this data cannot be used for statistical or trend analysis, but more for identifying vulnerabilities and gain a better understanding of the root causes of incidents and should be considered to compliment the data generated by mandatory, statistical, and monitoring systems.

The aircraft related incidents with known SCFM system categories were analyzed. There were 20,874 SCFM-related incidents (or reports) for Part 121, 135 and 91 operations during the time period from January 1993 through December 2012. Seventy-three percent of reported incidents were for Part 121, 5% for Part 135, and 22% for Part 91. Prior to March 1997, Part 121 operations included aircraft with 30 or more seats. In March 1997, the definition of Part 121 operations changed and now includes those aircraft with ten or more seats.

The SCFM categories used in the analysis are the following, in alphabetical order:

1. Automated Flight Controls
2. Brakes
3. Communication
4. Control Surface
5. Electrical / Power
6. Environmental Control System
7. Fuel System
8. Furnishings and Equipment
9. Hydraulics / Pneumatic
10. Icing
11. Landing Gear
12. Miscellaneous
13. Monitoring and Management
14. Navigation
15. Oil System
16. Propulsion System
17. Structures
18. Weather System

The aircraft related incidents were further identified in the ASRS dataset as having either critical or less severe aircraft equipment problems. When aircraft related incidents were caused by system component failure or malfunction, about 76% of the time they were identified as having a critical aircraft equipment problem. In addition to aircraft equipment problems, ASRS data provided the event results of the aircraft related incidents. The incidents can result in maintenance action, in unrelated maintenance action, or contained no information. For years prior to 1999, the maintenance action was not recorded in ASRS. Therefore, there were only 9,822 SCFM-related incident reports available. The incidents resulting in maintenance action were applicable to the "Maintain Vehicle Safety between Major Inspections (MVS)" Technical Challenge. As such, they were included in the analyses.

Results

Analysis of trends in the number of aircraft related incidents with known SCFM over the past 20 years (January 1993 through December 2012) can be seen in Figure 20. Part 121 had fewer reported incidents during 1993-1997, got higher during 1998-2002, dropped slightly during 2003-2007, and increased significantly during 2008-2012. Part 135 had a slight decreasing trend from 1993 to 2007, but a slight increase during the past 5 years. The slight decrease from 1993-1997 to 1998-2002 may be due to the definition change in March 1997 making a shift from Part 135 volume to Part 121 volume. Part 91 had a rather flat trend from 1993 to 2007, but had an increase during the past 5 years.

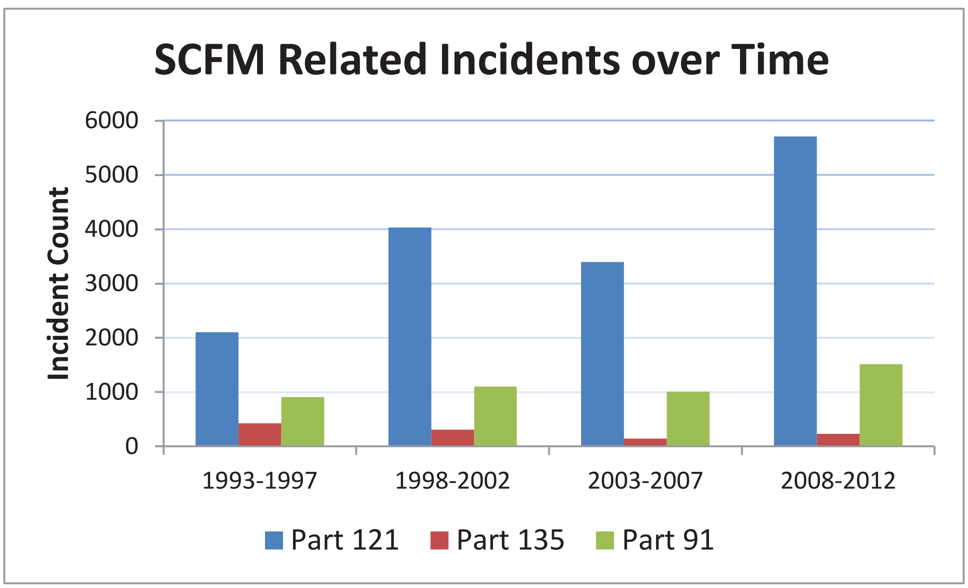
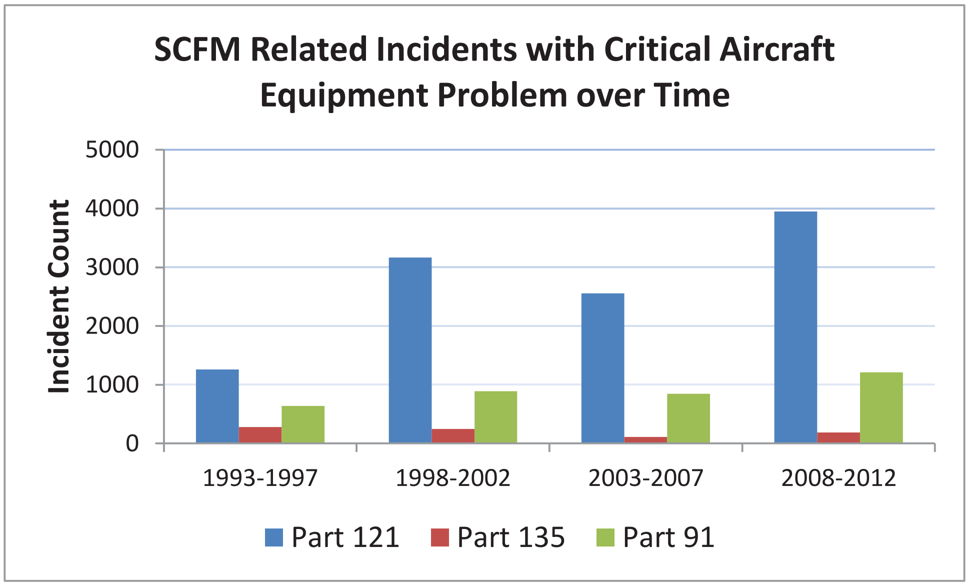


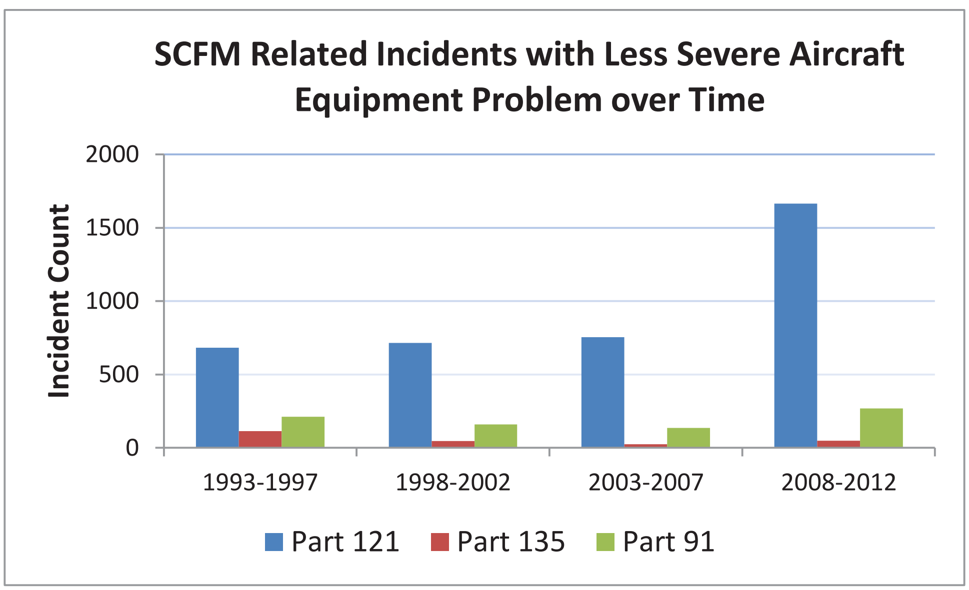
Figure 20. Incidents related to SCFM over four time periods

The number of incidents related to SCFM with an identified aircraft equipment problem over the time periods can be seen in Figure 21. Trends for critical equipment problem were similar to those without identified equipment problem (Figure 20). For less severe equipment problem (Figure 21b), Part 121 stayed rather flat from 1993 to 2007, and increased significantly during 2008-2012. Part 135 had a similar trend as its critical equipment problem. Part 91 had a slightly decreasing trend from 1993 to 2007, and had a significant increase during the past 5 years.

The number of incidents related to SCFM resulting in maintenance action over the time periods can be seen in Figure 22. Part 121 had fewer reported incidents during 2003-2007, and an increased trend during 2008-2012. Part 135 had a slightly decreasing trend from 1999 to 2002, and a flat trend from 2003 to 2012. Part 91 had a rather flat trend from 1999 to 2012.



(a) Critical aircraft equipment problem



(b) Less severe aircraft equipment problem

Figure 21. Incidents related to SCFM with identified aircraft equipment problem over four time periods

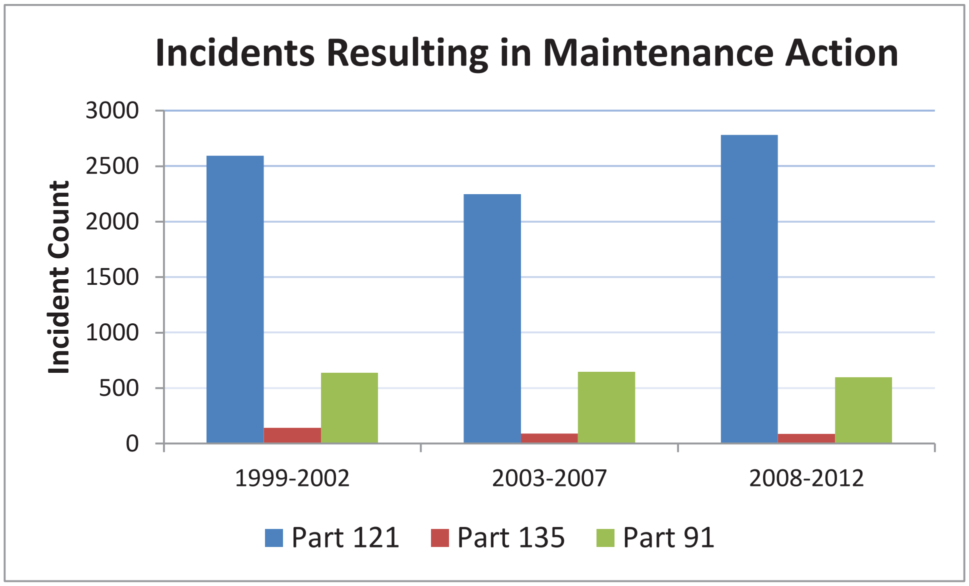


Figure 22. Number of incidents resulting in maintenance action over three time periods

Analysis of trends in the number of incidents broken down by SCFM category is assessed next. Table 8 compares SCFM categories with different identified aircraft equipment problems. Because each level of equipment problems had different numbers of incidents, percent incidents by SCFM categories were computed with respect to each equipment problem. Therefore, the total percent over all categories for any given equipment problem and any given FAR Part is 100 percent. The SCFM tall poles (highlighted cells) for incidents identified as having critical aircraft equipment problems were the same as those for all incidents regardless of aircraft equipment problems (i.e., column "Critical + Less Severe") across all FAR Parts.

For incidents with critical aircraft equipment problems, Part 121 had propulsion system, control surface, and monitoring and management as the top three tall poles. Part 135 had propulsion system, landing gear, and monitoring and management as the top three tall poles. Part 91 had propulsion system, landing gear, and electrical or power as the top three tall poles. Across all FAR Parts, propulsion system was the tallest pole.

For Part 121, when control surface and monitoring and management were the causes of incidents, they could be identified as either critical or less severe equipment problems. When navigation was the cause of incidents, it was always identified as less severe.

For Part 135, when landing gear and monitoring and management were the causes of incidents, they could be identified as either critical or less severe equipment problems. When communication was the cause, it was always identified as less severe.

For Part 91, when electrical or power was the cause, it could be identified as either critical or less severe equipment problems. When landing gear was the cause, it was always identified as a critical equipment problem. When communication, monitoring and management, and navigation were the causes, they were always identified as less severe.

Table 8. Percent incidents by SCFM categories for different aircraft equipment problems (with tall poles highlighted)

SCFM categories	Aircraft equipment problem for Part 121			Aircraft equipment problem for Part 135			Aircraft equipment problem for Part 91		
	Critical	Less Severe	Critical + Less Severe	Critical	Less Severe	Critical + Less Severe	Critical	Less Severe	Critical + Less Severe
Automated Flight Controls	3%	7%	4%	3%	5%	3%	3%	8%	4%
Brakes	2%	2%	2%	4%	3%	3%	5%	3%	5%
Communication	1%	5%	2%	2%	15%	5%	3%	25%	7%
Control Surface	11%	11%	11%	5%	6%	5%	4%	3%	4%
Electrical / Power	8%	5%	7%	8%	1%	6%	13%	11%	13%
Environmental Control System	10%	7%	9%	5%	6%	5%	4%	1%	3%
Fuel System	3%	2%	3%	4%	2%	3%	5%	2%	5%
Furnishings and equipment	2%	4%	2%	1%	3%	1%	1%	1%	1%
Hydraulics / Pneumatic	10%	5%	8%	3%	1%	3%	2%	1%	2%
Icing	1%	1%	1%	1%	0%	1%	1%	0%	1%
Landing Gear	7%	8%	7%	16%	12%	15%	18%	8%	16%
Miscellaneous	1%	2%	2%	0%	8%	3%	1%	2%	1%
Monitoring and management	11%	13%	11%	14%	17%	14%	7%	11%	7%
Navigation	4%	16%	8%	3%	11%	5%	3%	12%	5%
Oil System	3%	1%	3%	3%	0%	2%	3%	1%	2%
Propulsion System	17%	6%	14%	23%	6%	19%	26%	5%	22%
Structures	4%	5%	4%	5%	6%	6%	4%	5%	4%
Weather system	0%	1%	0%	0%	0%	0%	0%	0%	0%

Table 9 compares percent incidents caused by SCFM breakdown, whether or not the incident results in maintenance action. The same top three SCFM tall poles for each FAR Part were observed regardless of the incidents results (i.e., with or without maintenance action). Part 121 had propulsion system, control surface, and monitoring and management as the top three tall poles. Part 135 had propulsion system, landing gear, and monitoring and management as the top tall poles. Part 91 had propulsion system, landing gear, and electrical or power as the top three tall poles. Across all FAR Parts, propulsion system was the tallest pole.

Table 9. Percent incidents by SCFM categories with incidents results (with top three tall poles highlighted)

SCFM categories	Incident results for Part 121		Incident results for Part 135		Incident results for Part 91	
	Maintenance action	All results	Maintenance action	All results	Maintenance action	All results
Automated Flight Controls	3%	4%	2%	3%	4%	4%
Brakes	2%	2%	5%	3%	6%	5%
Communication	2%	2%	3%	5%	4%	7%
Control Surface	13%	11%	6%	5%	4%	4%
Electrical / Power	8%	7%	7%	6%	14%	13%
Environmental Control System	10%	9%	6%	5%	3%	3%
Fuel System	3%	3%	4%	3%	5%	5%
Furnishings and equipment	2%	2%	2%	1%	1%	1%
Hydraulics / Pneumatic	9%	8%	3%	3%	2%	2%
Icing	1%	1%	1%	1%	1%	1%
Landing Gear	8%	7%	18%	15%	18%	16%
Miscellaneous	1%	2%	0%	3%	1%	1%
Monitoring and management	12%	11%	13%	14%	7%	7%
Navigation	4%	8%	3%	5%	3%	5%
Oil System	3%	3%	5%	2%	3%	2%
Propulsion System	15%	14%	19%	19%	20%	22%
Structures	5%	4%	4%	6%	5%	4%
Weather system	0%	0%	0%	0%	0%	0%

In addition to trends over time periods and trends by SCFM category, trends as an association between time periods and SCFM category are analyzed next. The percentages of incidents by SCFM category for all four time periods were summarized in Figures 23 and 24. Because each time period had different numbers of reported incidents, the percentages of incidents by categories were computed with respect to each period. As such, the total percentage over all SCFM categories for any given time period is 100 percent.

SCFM categories	Aircraft equipment problem for Part 121												Aircraft equipment problem for Part 135				Aircraft equipment problem for Part 91							
	Critical				Less Severe				Critical + Less Severe				Critical + Less Severe				Critical				Critical + Less Severe			
	1993-1997	1998-2002	2003-2007	2008-2012	1993-1997	1998-2002	2003-2007	2008-2012	1993-1997	1998-2002	2003-2007	2008-2012	1993-1997	1998-2002	2003-2007	2008-2012	1993-1997	1998-2002	2003-2007	2008-2012	1993-1997	1998-2002	2003-2007	2008-2012
1	4%	3%	3%	3%	10%	12%	5%	5%	6%	5%	3%	4%	1%	5%	4%	5%	2%	2%	4%	3%	3%	4%	5%	4%
2	3%	2%	1%	2%	2%	2%	2%	2%	2%	2%	2%	2%	3%	3%	2%	5%	3%	6%	6%	5%	3%	5%	6%	5%
3	1%	1%	1%	1%	10%	6%	3%	3%	4%	2%	2%	2%	5%	6%	6%	1%	6%	2%	3%	1%	15%	8%	5%	2%
4	7%	11%	12%	12%	6%	9%	13%	12%	6%	11%	12%	12%	5%	2%	9%	6%	2%	3%	3%	5%	2%	2%	4%	5%
5	7%	7%	8%	8%	4%	5%	6%	6%	6%	7%	8%	8%	6%	6%	6%	7%	14%	15%	14%	12%	13%	14%	13%	11%
6	10%	11%	11%	10%	6%	8%	9%	6%	8%	11%	10%	9%	4%	5%	6%	8%	3%	4%	4%	4%	2%	3%	3%	4%
7	3%	3%	3%	3%	2%	2%	3%	3%	3%	3%	3%	3%	2%	5%	2%	5%	5%	6%	5%	4%	4%	5%	5%	4%
8	2%	2%	2%	2%	2%	7%	3%	3%	2%	3%	2%	2%	1%	1%	2%	2%	1%	0%	1%	1%	1%	0%	1%	1%
9	6%	8%	9%	13%	2%	1%	6%	8%	4%	6%	8%	12%	3%	2%	1%	5%	0%	1%	2%	3%	0%	1%	2%	3%
10	1%	1%	1%	2%	0%	1%	1%	1%	1%	1%	1%	1%	0%	0%	1%	3%	1%	2%	1%	1%	1%	1%	0%	1%
11	10%	7%	6%	7%	8%	5%	9%	10%	9%	6%	7%	8%	15%	17%	17%	12%	19%	18%	18%	16%	15%	16%	17%	16%
12	1%	1%	2%	1%	3%	5%	2%	1%	2%	2%	2%	1%	7%	2%	0%	0%	1%	1%	1%	1%	3%	2%	1%	0%
13	16%	13%	11%	8%	14%	10%	12%	15%	14%	12%	11%	10%	18%	17%	9%	8%	9%	7%	5%	6%	8%	7%	6%	8%
14	4%	4%	5%	4%	17%	18%	12%	15%	11%	7%	7%	8%	5%	3%	5%	8%	2%	2%	3%	3%	4%	5%	5%	5%
15	3%	3%	4%	3%	1%	0%	1%	1%	2%	3%	3%	3%	1%	2%	5%	3%	1%	3%	2%	3%	1%	2%	2%	3%
16	18%	18%	17%	17%	7%	4%	7%	6%	13%	15%	14%	13%	19%	18%	19%	18%	28%	24%	25%	27%	22%	20%	22%	24%
17	5%	5%	4%	4%	6%	4%	5%	5%	5%	4%	4%	4%	5%	7%	7%	4%	3%	4%	4%	4%	3%	4%	4%	4%
18	0%	0%	0%	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

1	Automated Flight Controls	10	Icing
2	Brakes	11	Landing Gear
3	Communication	12	Miscellaneous
4	Control Surface	13	Monitoring and management
5	Electrical / Power	14	Navigation
6	Environmental Control System	15	Oil System
7	Fuel System	16	Propulsion System
8	Furnishings and equipment	17	Structures
9	Hydraulics / Pneumatic	18	Weather system

Figure 23. Incidents (%) by SCFM category with aircraft equipment problem over time (with tall poles highlighted)

SCFM categories	Incident results for Part 121								Incident results for Part 91							
	Maintenance Action				All results				Maintenance Action				All results			
	1993-1997	1998-2002	2003-2007	2008-2012	1993-1997	1998-2002	2003-2007	2008-2012	1993-1997	1998-2002	2003-2007	2008-2012	1993-1997	1998-2002	2003-2007	2008-2012
Automated Flight Controls		4%	3%	3%	6%	5%	3%	4%		3%	4%	4%	3%	4%	5%	4%
Brakes		2%	2%	2%	2%	2%	2%	2%		6%	6%	5%	3%	5%	6%	5%
Communication		2%	2%	1%	4%	2%	2%	2%		6%	4%	2%	15%	8%	5%	2%
Control Surface		12%	14%	12%	6%	11%	12%	12%		3%	4%	6%	2%	2%	4%	5%
Electrical / Power		7%	9%	9%	6%	7%	8%	8%		17%	14%	13%	13%	14%	13%	11%
Environmental Control System		12%	10%	7%	8%	11%	10%	9%		4%	3%	3%	2%	3%	3%	4%
Fuel System		3%	3%	3%	3%	3%	3%	3%		4%	5%	6%	4%	5%	5%	4%
Furnishings and equipment		2%	2%	2%	2%	3%	2%	2%		0%	1%	0%	1%	0%	1%	1%
Hydraulics / Pneumatic		7%	8%	12%	4%	6%	8%	12%		1%	2%	2%	0%	1%	2%	3%
Icing		1%	1%	1%	1%	1%	1%	1%		1%	0%	1%	1%	1%	0%	1%
Landing Gear		6%	8%	9%	9%	6%	7%	8%		15%	19%	19%	15%	16%	17%	16%
Miscellaneous		1%	2%	1%	2%	2%	2%	1%		1%	1%	1%	3%	2%	1%	0%
Monitoring and management		12%	12%	11%	14%	12%	11%	10%		7%	5%	8%	8%	7%	6%	8%
Navigation		4%	4%	4%	11%	7%	7%	8%		4%	2%	3%	4%	5%	5%	5%
Oil System		3%	3%	3%	2%	3%	3%	3%		3%	3%	3%	1%	2%	2%	3%
Propulsion System		16%	15%	13%	13%	15%	14%	13%		20%	21%	19%	22%	20%	22%	24%
Structures		4%	4%	5%	5%	4%	4%	4%		5%	5%	5%	3%	4%	4%	4%
Weather system		0%	0%	0%	0%	0%	0%	0%		0%	0%	0%	0%	0%	0%	0%

Figure 24. Incidents (%) by SCFM category with event results over time (with tall poles highlighted)

For Part 121, the tall poles changed slightly over the time periods for combined aircraft equipment problem (as shown by highlighted cells in column "Critical + Less Severe" of Figure 23). Propulsion system (#16) and monitoring and management (#13) were two consistent tall poles over the past 20 years. Control surface (#4) became a tall pole in the past 15 years. Navigation (#14) was a tall pole in 1993-1997, but was not a tall pole in the past 15 years. Environmental control system (#6) was a tall pole from 1998 to 2007, but was not a tall pole in other periods. Hydraulics or pneumatic (#9) recently became a tall pole during 2008-2012.

When breaking the incidents into the ones with critical aircraft equipment problem, Part 121 tall poles changed slightly over the time periods (as shown by highlighted cells in column "Critical" of Figure 23). Propulsion system (#16) and environmental control system (#6) were two of the tall poles from 1993 to 2012, with propulsion system being the tallest pole. Monitoring and management (#13) was one of the tall poles in 1993-2007, but was not a tall pole in the last 5 years. Control surface (#4) became a tall pole in the past 15 years. Hydraulics/ pneumatic (#9) recently became a tall pole in the past 5 years. Landing gear (#11) was one of the tall poles from 1993 to 1997, but was not a tall pole in the past 15 years. The significant increase in the number of incident reports during 2007-2012 (from Figure 21a) was due to a noticeably significant increase in the percentage of hydraulics/ pneumatic (#9) problems.

For less severe equipment problem, the Part 121 top three tall poles changed slightly over the time periods (column "Less Severe" in Figure 23). Navigation (#14) and monitoring and management (#13) were two of the tall poles in 1993-2012. Control surface (#4) became a tall pole in the past 10 years. Automatic flight controls (#1) were a tall pole from 1993 to 2002, but were not a tall pole in the past 10 years. The significant increase in the number of incident reports during 2007-2012 (from Figure 21b) was not due to any specific SCFM category (no noticeable significant increase in percent by a particular category), but rather the tall poles were proportionally contributing to the increase in incidents.

For Part 135, the tall poles have changed slightly over the four time periods. Due to a small number of incident reports across all SCFM categories for both aircraft equipment problems, only the combined equipment problem ("Critical + Less Severe") was analyzed. Propulsion system (#16) and landing gear (#11) were two consistent tall poles over the past 20 years. Monitoring and management (#13) was a tall pole from 1993 to 2002, but was not a tall pole in the past 10 years.

For Part 91, tall poles have not changed significantly over the time periods for the combined equipment problem. Propulsion system (#16), landing gear (#11), and electrical or power (#5) were consistently three of the tall poles over the past 20 years. Communication (#3) was a tall pole in 1993-1997, but was not a tall pole in the past 15 years. Due to a small number of incidents across all SCFM categories for less severe equipment problem, its trend of the SCFM tall poles was excluded in the analysis. For Part 91 with critical equipment problems, the tall poles did not change in the past 20 years. Propulsion system (#16), landing gear (#11), and electrical or power (#5) were the top three tall poles for these time periods.

Generally, trends of the SCFM tall poles over time for incidents having a critical equipment problem were similar to those for all incidents regardless of aircraft equipment problems for Parts 121 and 91. This may be because 76% of all incidents were the ones with a critical equipment problem.

Figure 24 shows the breakdown of incidents by SCFM category considering the results of the incidents (with or without maintenance action). Trends of the SCFM tall poles over time for all FAR Parts for all incident results (i.e., with or without maintenance action) were the same as those in column "Critical + Less Severe" equipment problem of Figure 23. However, they were reported in this figure to facilitate the comparison. Due to the small number of incidents, Part 135 was excluded. Clearly, trends of the SCFM tall poles over time for incidents resulting in maintenance action were the same as those for all results for Parts 121 and 91.

For Part 121, the tall poles had changed slightly over the three time periods for incidents resulting in maintenance action. Propulsion system, control surface, and monitoring and management constantly were the top three tall poles from 1999 to 2012. Hydraulics or pneumatic recently became a tall pole during 2008-2012. Environmental control system was a tall pole from 1999 to 2007, but was not a tall pole from 2008 to 2012. For Part 91 (Figure 24), the tall poles did not change from 1999 to 2012. Propulsion system, landing gear, and electrical or power were the top three tall poles across all three time periods.

3. REVIEW OF VEHICLE HEALTH MANAGEMENT (VHM) ISSUES AND FUTURE RESEARCH NEEDS

This section contains a review of subject matter experts' safety priority lists and research studies pertaining to VHM issues. The study specifically focuses on VHM issues related to the MVS Technical Challenge (TC2).

3.1. CAST Safety Enhancements Reserved for Future Implementation (SERFIs)

The Commercial Aviation Safety Team (CAST) was established in 1998 in response to several commercial aviation accidents in the late 1990s (Ref. 5). It applies an integrated, data-driven strategy to reduce commercial aviation fatality risk in the United States and promote new government and industry safety initiatives throughout the world.

Under the direction of a government and an industry co-chair, CAST sets overall policy and oversees the activities of the following working groups: Joint Safety Analysis Teams (JSATs) and Joint Safety Implementation Teams (JSITs). JSATs perform in-depth data analyses of a particular accident category, and then identify intervention strategies to eliminate potential precursors and contributing factors to the accidents. JSITs develop safety enhancements based on the intervention strategies identified by the JSATs (Ref. 6).

In addition to the current Safety Enhancements (SEs) in the CAST plan, there are 54 Safety Enhancements Reserved for Future Implementation (SERFIs), Research SERFIs, and Research & Development Safety Enhancements (R&D SEs) that were developed by various JSIT activities but were not approved by CAST for implementation on the active Safety Plan.

An assessment of the CAST SERFIs against the MVS research products was conducted. The result of this assessment determined that MVS products are aligned with only one SERFI: R&D Safety Enhancement 118, Health and Usage Monitoring Systems (HUMS). HUMS is a R&D project focused on preventing Approach and Landing Accident Reduction (ALAR) accidents and incidents in commercial aviation (Refs. 7, 8, 9). While it contains high ratings of overall effectiveness and feasibility, HUMS was considered by the JSIT to require additional research before realizing the full potential to reduce accidents. As such, it was recommended to CAST as a research project, and it became a Safety Enhancement Reserved for Future Implementation (SERFI).

Because SE 118 was recommended for research, a Detailed Implementation Plan delineating specific actions and outputs, identifying responsible organizations, and estimating financial resources required for completion was never developed. The JSIT merely developed the following Statement of Work outline for the HUMS project:

Conduct research and develop technology for:

- Detection, prediction and/or annunciation of impending equipment failures.
- Detection and annunciation of inappropriate settings that may affect safe flight.
- Real time decision making support for maintenance and operations.
- Smart alerting systems that provide real time assistance to flight crews with on-board system failures and include diagnostics, prioritization schemes and elimination of nuisance alerts.

MVS products applicable to SE 118 are: Hybrid Structural Damage Diagnosis (MVS-1.1), Vehicle Integrated Propulsion Research (MVS-2.1), Mitigating Turbomachinery Structural Failure (MVS-2.2), Vehicle Level Diagnostics and Integration (MVS-3.1), and Physics-Based Models and Algorithms for Wiring Fault Detection (MVS-3.2).

3.2. NTSB Most-Wanted List

Every year the NTSB publishes a most-wanted list of transportation safety priorities for various transportation modes (e.g., aviation, highway, etc.) Although most of the NASA AvSP research is directed toward commercial aircraft operations, a portion of the work in MVS may be applicable to the issue of "Improve General Aviation Safety", which is currently on the NTSB's Most Wanted List (Ref. 10). A specific recommendation that may relate to MVS research is:

"Aircraft maintenance workers should also be required to undergo recurrent training to keep them up to date with the best practices for inspecting and maintaining electrical systems, circuit breakers, and aged wiring."

In addition, the NTSB also issues safety recommendations as a result of accident investigations and other safety concerns that arise. Some recent open recommendations (during 2008-2013) that may be related to MVS research are listed in Table 10.

Table 10. Recent NTSB Safety Recommendations related to MVS research

Recommendation #	Recommendation
A-13-001	Establish duty-time regulations for maintenance personnel working under 14 Code of Federal Regulations Parts 121, 135, 145, and 91 Subpart K that take into consideration factors such as start time, workload, shift changes, circadian rhythms, adequate rest time, and other factors shown by recent research, scientific evidence, and current industry experience to affect maintenance crew alertness.
A-13-002	Encourage operators and manufacturers to develop and implement best practices for conducting maintenance under 14 Code of Federal Regulations Parts 135 and 91 Subpart K, including, but not limited to, the use of work cards for maintenance tasks, especially those involving safety-critical functions, that promote the recording and verification of delineated steps in the task that, if improperly completed, could lead to a loss of control.
A-13-003	Require that personnel performing maintenance or inspections under 14 Code of Federal Regulations Parts 121, 135, 145, and 91 Subpart K receive initial and recurrent training on human factors affecting maintenance that includes a review of the causes of human error, including fatigue, its effects on performance, and actions individuals can take to prevent the development of fatigue.
A-12-068	Develop fire detection system performance requirements for the early detection of fires originating within cargo containers and pallets and, once developed, implement the new requirements.
A-10-096	Require that mechanics performing required inspection item and other critical tasks receive on-the-job training or supervision when completing the maintenance task until the mechanic demonstrates proficiency in the task.

3.3. NRC Decadal Survey of Civil Aeronautics

The National Research Council (NRC) is a part of the National Academy of Sciences with the purpose of advising the government on matters of science and technology. It was organized in 1916 and has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering. The NRC conducted a decadal survey of civil aeronautics to assist NASA in developing a decadal strategy for federal aeronautics research in 2006 (Ref. 11). The report describes research that is deemed necessary to further the state of the art in areas consistent with NASA's legislative charter resulting in significant long term impact on national aeronautics. The survey study prioritized the identified research & technology (R&T) challenges in terms of supporting infrastructure, mission alignment, lack of alternative sponsors, and appropriate risk level according to NASA's civil aeronautics research program. The NRC examined a total of 89 distinct R&T challenges that were categorized into five R&T areas. The five areas were

A: Aerodynamics and aero acoustics.
B: Propulsion and power.
C: Materials and structures.
D: Dynamics, navigation, and control, and avionics.
E: Intelligent and autonomous systems, operations and decision making, human integrated systems, and networking and communications.

Assessment of R&T challenges against the MVS research products was conducted. Table 11 presents only the R&T challenges applicable to the MVS. For each challenge, numeric value following the letter of the R&T area indicates the NASA priority. The smaller the numeric, the higher the priority the challenge had.

Table 11. R&T Challenges applicable to the MVS TC

Challenge	R&T Area	Description
B3	Propulsion and power	Intelligent engines and mechanical power systems capable of self-diagnosis and reconfiguration between shop visits
C1	Materials and structures	Integrated vehicle health management
D5	Dynamics, navigation, and control, and avionics	Fault tolerant and integrated vehicle health management systems

The committee also identified two key barriers to achieving the aeronautics objectives: (1) certification and (2) change management. As systems become more complex and nondeterministic, methods to certify new technologies become more difficult to validate. It is essential for NASA, with collaboration with the FAA, to conduct research on certification methods and on methods to introduce the anticipated change.

3.4. Future Aviation Safety Team Areas of Change

The European Commercial Aviation Safety Team (ECAST) and the Commercial Aviation Safety Team (CAST) in the USA sponsor the Future Aviation Safety Team (FAST) (Ref. 12). FAST performs analyses of ongoing and future changes affecting the global aviation system with the goal of revealing unidentified safety hazards. Beginning in 2001, FAST compiled a database of Areas of Change (AoC). An AoC is defined as "any phenomenon that will affect the safety of the aviation system either from within or from important domains external to aviation" (Ref. 13). The current database that contains AoC was recently updated on November 15, 2013. Potential safety hazards associated with each AoC are also available in the database. Table 12 presents AoCs that are related to the MVS Technical Challenge. Some of the hazards cited include:

- high complexity vehicle health management systems that are unable to yield to software certification techniques that exist today
- failure to detect aircraft structural damage due to particle shedding, de-lamination, and high-current lightning strikes
- certification challenges due to non-deterministic nature of Artificial Intelligence outputs from integrated modular architecture
- the shortage of certified maintenance personnel
- inadequate maintenance skills and trainings
- crew's fatigue causing maintenance errors.

Table 12. Future Aviation Safety Team Areas of Change applicable to the MVS TC (Ref. 13)

AoC Number - Title	Description	Potential Hazards
14 - Advanced vehicle health management systems	Future vehicle health systems may be based on continuously updated vehicle state matrices derived from networks of multiple sensors. Advanced software models incorporating the functional characteristics of the vehicle may process the sensor network outputs.	• Systems of such complexity that they are unable to yield to software certification techniques that exist today. In some cases it is not the software itself that is the issue; it is the failed logic that drives annunciations and/or changes especially following system degradation/failures. • Sensors continuing to be the lowest reliability components and therefore need to be redundant to obtain the required system safety • Sensor failures producing single point failure of multiple devices
39 – Increasing use of composite structural materials	The use of composites will continue to increase in aircraft structures.	• Failure to detect sub-surface damage and de-lamination • Shedding of micron-sized particles due to fatigue and chafing • Damage due to high-current lightning strikes

Table 12. (Continued)

AoC Number - Title	Description	Potential Hazards
185 – Introduction of Non-Deterministic Approaches (NDA) and artificial intelligence (AI; i.e. self-learning) in aviation systems	Complex engineered products are more likely to meet performance requirements when NDA are used. Aircraft structural health management has always relied upon NDA. Management of the Next Generation Air Transportation System (NextGen) will use NDA for trajectory-based operations (TBO) to account for aircraft position and weather uncertainty. Future flight decks may contain, or be expected to interact with, software "intelligent agents." The characteristics of these agents may differ significantly from most software tools in use today. The increasing complexity of technology drives the need for such NDA.	• Certification challenges due to non-deterministic nature of AI outputs from integrated modular architectures • Pilots not understanding intent and actions of AI avionics • Failure to achieve robustness, as defined under DO-178C[1] guidelines – the very specific proof that under all application failure conditions, a single failure in one partition will not affect other partitions.

[1] DO-178C is Software Considerations in Airborne Systems and Equipment Certification. This replaces DO-178B as the primary document by which the certification authorities such as FAA, EASA and Transport Canada will approve all commercial software-based aerospace systems. The new document is called DO-178C/ED-12C and was completed in November 2011 and approved by the RTCA, Inc. in December 2011. It became available for sale and use in January 2012. RTCA, Inc. (known as Radio Technical Commission for Aeronautics, originally founded in 1935, and until its re-incorporation in 1991 as a private not-for-profit corporation) is a US volunteer organization that develops technical guidance for use by government regulatory authorities and by industry. It has over 200 committees and overall acts as an advisory body to the FAA.

Table 12. (Continued)

AoC Number - Title	Description	Potential Hazards
226 – Changes in the qualifications of maintenance personnel	The shortage of certified maintenance personnel may result in lower quality servicing and maintenance of aircraft with a concomitant reduction in the reliability of both new and aging aircraft. Servicing of advanced avionics will require specialized skills, yet training in disciplines such as composite material repair, nondestructive inspection, solid-state electronics/avionics/built-in test equipment, principles of troubleshooting and human factor is currently only an option within maintenance training curricula. As the number of non-certified staff increases, the need to check their work increases.	• Acceptance of poor quality work either because of time limitations or because errors are not detected. • Reduction in the availability of certified maintenance personnel due to tightening of controls on maintenance procedures, limitation of working hours, vision tests, etc. • Reduction in the number of experienced maintenance inspectors.

Table 12. (Continued)

AoC Number - Title	Description	Potential Hazards
230 - Paradigm shift from paper based to electronic based maintenance records and databases	In the future, complex, integrated aircraft will require more and more automation for fault detection, diagnosis, and resolution. In addition, new diagnostic and prognostic safety analysis will require electronic tracking of maintenance findings and actions.	• Degradation in maintenance quality of legacy aircraft which were previously paper-based but are transitioning to a computerized format • Inappropriate skill sets among maintenance personnel because of changing processes, tools, and techniques to support the new computerized systems • Poor task verification processes • Lack of coordination between maintenance and flight crews • Disconnect in processes for handling the formal aircraft log; manual, via automation • Failure of processes to fully inform crew of inadequate pre-flight aircraft status due to new electronic log entry formats; mismatches between manual, paper logs and electronic logs • As with any digital system, it is not enough to make “digital” copies of paper (scanning, PDFs). It is critical to build in “smart” tags, indexes and cross-references so information can be navigated and “found.” • Loss of access to existing maintenance information during transition process to electronic records. • Cumbersome access to historic maintenance records required to be kept by aircraft owner.

Table 12. (Continued)

AoC Number - Title	Description	Potential Hazards
236 - Increasing use of virtual mockups for maintenance training and for evaluation of requirements	Digital/electronic mock-ups are now being adopted by the industry as substitutes for the physical mock-ups. It should be recognized that the current digital mock-up capability together with available human modeling capability does not permit total maintenance/assembly task simulation (perhaps 2-5 years away). While any safety related risk is low, if a situation is not recognized during design phase, it will not emerge or be addressed until assembly of first aircraft. This results in a cost/schedule penalty and aircraft maintainability issues.	• Maintenance errors arising from differences between the training environment and real line operations. • Failure to maintain configuration control between maintenance simulators and actual aircraft physical hardware. This should not be a hazard if: • The use of various levels of simulation are carefully assessed and used accordingly. • Assessment should include testing that ensures there is no negative transfer of learning from simulator to operations.

Table 12. (Continued)

AoC Number - Title	Description	Potential Hazards
241 - Operational tempo and economic considerations affecting fatigue among maintenance personnel	As result of increased financial pressure on airlines over the last 10-15 years there have been changes in the way maintenance organizations conduct their work. The number of maintenance employees per aircraft has been reduced significantly even taking into consideration that the present fleet demands less maintenance due to increased quality and more efficient maintenance programs. Only in specific maintenance tasks such as primary flight control work this ratio is still more or less normal. For almost all other tasks there are now just spots checks of 10-15% of the work actually performed by someone else. Contract maintenance personnel have economic incentives to seek out overtime to maximize their income. A large number of countries still have not set maximum duration working times for maintenance staff like there are for pilots. Due to tight daytime flight schedules, there is increasing pressure for nightshift operations (there is a known safety risk when working under pressure in night hours on complicated work) on the involved maintenance organization.	• Reduction in staff, economic incentives available to maintenance technicians plus shifts toward night schedules for critical maintenance increase the likelihood of fatigue and maintenance errors. Due to tight daytime flight schedules, there is increasing pressure for nightshift operations on the involved maintenance organization. • Many countries still have not set maximum duration working times for maintenance staff like there are for pilots. • Number of maintenance employees per aircraft has been reduced significantly. Only in specific maintenance tasks such as primary flight control work is this ratio is still more or less normal. • Based on aircraft sales forecasts in non-Western markets, there will be a worldwide shortage of qualified maintenance personnel. • The loss of experience, safety culture, and tribal knowledge may be a bigger issue than overwork and fatigue.

Table 12. (Continued)

AoC Number - Title	Description	Potential Hazards
251 – Introduction of new training methodologies for maintenance staff	IATA[2] Training and Qualification Initiative (ITQI) for Maintenance is a recent IATA initiative. It is centered on competency based training and assessment. This will require the definition of competencies. An approach has been validated through meetings with original equipment manufacturers, airline maintenance and training organizations. IATA has worked closely with ICAO to develop this material. The Air Navigation Council (ANC) was briefed in January 2010 on the progress.	Lack of ICAO guidance material on how competency based training can be applied to maintenance.

[2] International Air Transport Association (IATA) is an international trade association for the world's airlines (240 airlines or 84% of total air traffic) (ref. 22). IATA is actively promoting flight safety in safety auditing, infrastructure safety, safety data management and analysis, integrated airline management system, flying operations, and cargo and dangerous goods safety.

Table 12. (Continued)

AoC Number - Title	Description	Potential Hazards
256 - Decreasing availability of qualified maintenance staff at stations other than home base of operation	Increasing financial pressure on airlines is resulting in steady reductions of maintenance staff at out stations. As a result of this phenomenon, flight crew is increasingly reluctant to report aircraft defects when away from home base. Statistics bear this out. A 2009 Airline Engineers International survey revealed that airlines, including majors reported inbound defects as high as 94% over only 6% outbound defects. Until recently, such behavior may have resulted only in incidents, albeit that well documented cases are scarce. This phenomenon may have been a root cause of at least one recent accident (Turkish Airlines, Schiphol, 2009). One of the largest contract labor providers is in the process of recruiting labor from outside the United States. This organization is currently in the process of gaining Department of Labor and Immigration and Naturalization approval in order to offer jobs and obtain appropriate visas. One of the potential sources being investigated is the UK, where they are also experiencing a shortage of qualified aircraft maintenance technicians.	• Lack of timely servicing of aircraft with potentially flight-critical component or system problems. • Poor quality aircraft servicing due to hiring of minimally-qualified staff • Over-reliance on Minimum Equipment List (MEL) procedures as safety nets • Incorrect information on the MEL within the airline operation center • Inappropriate release of an aircraft by dispatch.

3.5. Naval Air Systems Command (NAVAIR)

Naval Air Systems Command (NAVAIR) of the United State Navy solicited for research proposals in four research areas during Fiscal Year 2013 (Ref. 14). Two out of four research areas were likely to be related to MVS: BAA 121 – Advanced Aircraft Power Systems (for research up to four years); and BAA 124 – Propulsion and Power System, Condition Based Maintenance, Prognostics, Diagnostics, and Health Monitoring (for research up to five years).

Under BAA 121, one of Navy power system needs was "diagnostics, prognostics, and health management for electrical power and wiring systems to bring about improvements in readiness, maintenance, safety, and cost" (Ref. 14).

Under BAA 124, Navy seeks to "develop propulsion and power system condition based maintenance, prognostic, diagnostic, and health monitoring technologies to improve aircraft safety, reliability, maintainability, affordability, and availability" (Ref. 14).

3.6. Industry

Several aerospace corporations are actively developing technology related to the MVS research: General Electric (GE) Sensing and Inspection Technologies (Ref. 15); Airplane Health Management services at Boeing (Refs. 16, 17); Aircraft Maintenance Analysis (AIRMAN) at Airbus (Refs. 18, 19, 20); and Health and Usage Management Systems (HUMS) at UTC Aerospace Systems (Ref. 21).

4. DISCUSSION AND CONCLUSIONS

NTSB accident data (1996-2010) and FAA incident data (1996-2010) were examined across four operational categories: Federal Aviation Regulations Part 121, Scheduled Part 135, Non-Scheduled Part 135, and Part 91. In addition, an analysis of the types of aircraft involved in the accidents and incidents was performed. The aircraft were divided into groups according to engine type. The system /component failure/malfunction (SCFM) data were examined both by operation category and by aircraft engine type.

In Part 121 operations, jet aircraft were involved in 81 percent of the accidents and 73 percent of the incidents. In contrast, Part 91 and Non-Scheduled Part 135 accidents and incidents occurred predominantly on aircraft with reciprocating engines. A large number of Scheduled Part 135 accidents (30 percent) and incidents (51 percent) occurred on turboprop aircraft. More than fifty percent of the jet fatalities occurred in accidents that included SCFM, compared with only thirteen percent of the fatalities in single-engine aircraft.

Twenty-two percent of multiple-engine (reciprocating) aircraft accidents involved SCFM; this was the highest percentage among all engine types. Interestingly, the lowest percentage was associated with single-engine (reciprocating) aircraft (14 percent). Among incidents, however, 58 to 61 percent of jet, turbo-prop, and multiple-engine (reciprocating) aircraft incidents involved SCFM, compared with 31 percent for single-engine incidents.

Across all flight categories (i.e., FAR Parts 121, 135, and 91), the most common systems involved in SCFM accidents and incidents were the engine and landing gear. In general, failures or malfunctions of either the landing gear or hydraulic systems result in less severe outcomes (fewer fatalities and less aircraft destruction) than other systems, whereas failures or malfunctions of either the structure or flight control systems result in more severe outcomes. Similar observations were found when accidents and incidents were examined by aircraft engine types.

The SCFM related incidents analysis of the ASRS dataset resulted in 20,874 reports during 1993-2012. Seventy-three percent of reported incidents were for Part 121, 22% for Part 91, and 5% for Part 135. The SCFM incidents were further identified in the ASRS dataset as having critical or less severe aircraft equipment problems. When aircraft related incidents were caused by system component failure or malfunction, about 76% of the time they were identified as having a critical aircraft equipment problem. In addition to aircraft equipment problems, ASRS data provided the event results of the aircraft related incidents. The incidents can result in maintenance action, in unrelated maintenance action, or contained no information. The incidents resulting in maintenance action were applicable to the MVS Technical Challenge. As such, they were included in the analyses.

For incidents with critical aircraft equipment problems, Part 121 had propulsion system, control surface, and monitoring and management as the top three SCFM categories (tall poles). Part 135 had propulsion system, landing gear, and monitoring and management as the top three tall poles. Part 91 had propulsion system, landing gear, and electrical or power as the top three tall poles. Across all FAR Parts, propulsion system was the tallest pole. The SCFM tall poles for all incidents regardless of aircraft equipment problems were the same as those for incidents identified as having a critical aircraft equipment problem across all FAR Parts.

For Part 121, when control surface and monitoring and management were the causes of incidents, they could be identified as either critical or less severe equipment problems. When navigation was the cause of incidents, it was always identified as less severe.

For Part 135, when landing gear and monitoring and management were the causes of incidents, they could be identified as either critical or less severe equipment problems. When communication was the cause, it was always identified as less severe.

For Part 91, when electrical or power was the cause, it could be identified as either critical or less severe equipment problems. When landing gear was the cause, it was always identified as critical equipment problem. When communication, monitoring and management, and navigation were the causes, they were always identified as less severe.

When comparing SCFM-related incidents, whether or not the incident results in maintenance action, the same top three SCFM tall poles for each FAR Part were observed. Part 121 had propulsion system, control surface, and monitoring and management as the top three tall poles. Part 135 had propulsion system, landing gear, and monitoring and management as the top three tall poles. Part 91 had propulsion system, landing gear, and electrical or power as the top three tall poles. Across all FAR Parts, propulsion system was the tallest pole.

An assessment of the CAST SERFIs against the MVS research products was conducted. The result of the assessment determined that MVS products are aligned with only one SERFI: R&D Safety Enhancement 118, Health and Usage Monitoring Systems (HUMS). Five out of six MVS products are applicable to SE 118, which are: Hybrid Structural Damage Diagnosis (MVS-1.1), Vehicle Integrated Propulsion Research (MVS-2.1), Mitigating Turbomachinery Structural Failure (MVS-2.2), Vehicle Level Diagnostics and Integration (MVS-3.1), and Physics-Based Models and Algorithms for Wiring Fault Detection (MVS-3.2).

The majority of aviation safety improvements on the 2012 NTSB Most-Wanted List as well as recent open safety recommendations from 2008 to 2013 related to the MVS Technical Challenge involve reduction of maintenance crew errors due to crew's fatigue and inadequate training.

The NRC Decadal Survey of Civil Aeronautics related to the MVS research products was assessed. The survey study prioritized the identified research & technology (R&T) challenges according to NASA's civil aeronautics research program. The NRC examined a total of 89 distinct R&T challenges. Three challenges applicable to the MVS Technical Challenge were: B3 – Intelligent engines and mechanical power systems capable of self-diagnosis and reconfiguration between shop visits; C1 – Integrated vehicle health management; and D5 – Fault tolerant and integrated vehicle health management systems. The committee also identified two key barriers to achieving the aeronautics objectives: (1) certification and (2) change management. As systems become more complex and nondeterministic, methods to certify new technologies become more difficult to validate. It is essential for NASA, with collaboration with the FAA, to conduct research on certification methods and on methods to introduce the anticipated change.

According to the Future Aviation Safety Team, areas of changes related to the MVS Technical Challenge are either vehicle-related or maintenance crew-related. Vehicle-related areas of changes were: AoC-14 Advanced vehicle health management systems; AoC-39 Increasing use of composite structural materials; and AoC-185 Introduction of Non-Deterministic Approaches (NDA) and artificial intelligence (self-learning) in aviation systems. Potential safety hazards associated with these vehicle-related areas of changes were: highly complex vehicle health management systems that are unable to yield to software certification techniques that exist today; failure to detect aircraft structural damage due to particle shedding, de-lamination, and high-current lightning strikes; and certification challenges due to non-deterministic nature of Artificial Intelligence outputs from integrated modular architecture. Several maintenance crew-related areas of changes were driven by the shortage of certified maintenance personnel, inadequate maintenance skills and trainings, and crew's fatigue causing maintenance errors.

Future research direction in the MVS Technical Challenge is evidently strong as seen from Fiscal Year 2013 research solicitations from NAVAIR, and MVS-related technologies actively being developed by aviation industry leaders, including GE, Boeing, Airbus, and UTC Aerospace Systems. Given the highly complex vehicle heath management systems, modifications can be made in the future so that the VSST technical challenges address inadequate maintenance crew's trainings and skills, and the certification methods of such systems as recommended by the NTSB, NRC, and FAST areas of change.

ACRONYMS

AIDS = Accident/Incident Data System
ALAR = Approach and Landing Accident Reduction
ASIAS = Aviation Safety Information Analysis and Sharing
ASRS = Aviation Safety Reporting System
AvSP = Aviation Safety Program
CAST = Commercial Aviation Safety Team
FAA = Federal Aviation Administration
FAR = Federal Aviation Regulations
FAST = Future Aviation Safety Team
HUMS = Health and Usage Monitoring Systems
IATA = International Air Transport Association
ICAO = International Civil Aviation Organization
JSAT = Joint Safety Analysis Team
JSIT = Joint Safety Implementation Team
MVS = Maintain Vehicle Safety between Major Inspections
NAVAIR = Naval Air Systems Command
NRC = National Research Council
NTSB = National Transportation Safety Board
R&D SE = Research & Development Safety Enhancement
SCFM = System Component Failures or Malfunctions
SE = Safety Enhancement
SERFI = Safety Enhancements Reserved for Future Implementation
VHM = Vehicle Health Management
VSST = Vehicle Systems Safety Technology Project

ACKNOWLEDGEMENT

We thank Dr. Sharon Monica Jones and Colleen A. Withrow for valuable comments.

REFERENCES

1. Krasa, P., and Graves, S., “Vehicle Systems Safety Technology (VSST) Project Plan,” National Aeronautics and Space Administration, February 1, 2013.
2. Gibson, J.E., Scherer, W.T., and Gibson, W.F., “How to Do Systems Analysis,” John Wiley & Sons, Inc., Hoboken, New Jersey, 2007.
3. National Transportation Safety Board, “Government Information Locator Service (GILS): Aviation Accident Synopses”’ http://ntsb.gov/Info/gils/gilssyn.htm.
4. ASRS: The Case for Confidential Incident Reporting Systems 2001, NASA ASRS Publication; http://asrs.arc.nasa.gov/docs/rs/60_Case_for_Confidential_Incident_Reporting.pdf, accessed February 4, 2014.
5. Commercial Aviation Safety Team, “The Commercial Aviation Safety Team,” 2011. http://www.cast-safety.org/.
6. Federal Aviation Administration, “Fact Sheet – Commercial Aviation Safety Team,” July 11, 2013. http://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=15214.
7. Joint Safety Analysis Team (JSAT), “Results and Analysis, Approach and Landing Accident Reduction (ALAR),” September 10, 1999.
8. Joint Safety Implementation Team (JSIT), “Results and Analysis, Approach and Landing Accident Reduction (ALAR),” May 17, 2001.
9. Commercial Aviation Safety Team, Approach and Landing Accident Reduction (ALAR) Joint Safety Implementation Team (JSIT), “Implementation Plan for Approach and Landing Health & Usage Monitoring Systems (HUMS),” October 1, 2002.
10. National Transportation Safety Board, “NTSB Most Wanted List – Improve General Aviation Safety,” November 14, 2012. http://www.ntsb.gov/safety/mwl5_2012.html, Accessed December 2013.
11. National Research Council, “Decadal Survey of Civil Aeronautics,” 2006.
12. Future Aviation Safety Team, http://www.nlr-atsi.nl/fast/, Accessed February 12, 2014.
13. Future Aviation Safety Team, “Areas of Change Catalog: Ongoing and Future Phenomena and Hazards Affecting Aviation”, http://www.nlr-atsi.nl/fast/FAST_AoCs_20131115.pdf, Accessed February 12, 2014.
14. “Guide to Naval Aviation Propulsion and Power Technology Development Programs,” Naval Air Systems Command, Propulsion and Power Engineering, Patuxent River, MD, October 2012.
15. “GE Sensing and Inspection Technologies,” http://www.ge-mcs.com/download/it-common/GEIT-10012EN_ndt-brochure.pdf, Accessed November 2013.
16. “The Boeing Edge -- Airplane Health Management,” http://www.boeing.com/boeing/commercial/aviationservices/information-services/real-time-operations/ahm.page, Accessed November 2013.

17. "The Boeing Edge – Real-Time Operations," http://www.boeing.com/boeing/commercial/aviationservices/information-services/real-time-operations/index.page?, Accessed November 2013.
18. "Airbus, The Leading Aircraft Manufacturer, AIRMAN real-time aircraft health monitoring", http://www.airbus.com/innovation/proven-concepts/in-fleet-support/airman/, Accessed November 2013.
19. "AIRTHM – Airbus Real Time Health Monitoring," http://www.airbus.com/support/maintenance-engineering/airthm/, Accessed November 2013.
20. "Airbus E-Solutions," http://www.airbus.com/support/maintenance-engineering/e-solutions/, Accessed November 2013.
21. "Sensors and Integrated Systems -- Health and Usage Management Systems (HUMS)," http://utcaerospacesystems.com/cap/products/Pages/health-usage-management-systems.aspx, Accessed November 2013.
22. International Air Transport Association, http://www.iata.org/about/Pages/index.aspx, Accessed February 13, 2014.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
01- 03 - 2014	Technical Memorandum	

4. TITLE AND SUBTITLE	**5a. CONTRACT NUMBER**
Identification of Vehicle Health Assurance Related Trends	
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
Phojanamongkolkij, Nipa; Evans, Joni K.; Barr, Lawrence; Leone, Karen; Reveley, Mary S.	**5e. TASK NUMBER**
	5f. WORK UNIT NUMBER
	284848.02.01.07.04

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
NASA Langley Research Center Hampton, VA 23681-2199	L-20382
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
National Aeronautics and Space Administration Washington, DC 20546-0001	NASA
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)
	NASA/TM-2014-218177

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 66
Availability: NASA CASI (443) 757-5802

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Trend analysis in aviation as related to vehicle health management (VHM) was performed by reviewing the most current statistical and prognostics data available from the National Transportation Safety Board (NTSB) accident, the Federal Aviation Administration (FAA) incident, and the NASA Aviation Safety Reporting System (ASRS) incident datasets. In addition, future directions in aviation technology related to VHM research areas were assessed through the Commercial Aviation Safety Team (CAST) Safety Enhancements Reserved for Future Implementations (SERFIs), the National Transportation Safety Board (NTSB) Most-Wanted List and recent open safety recommendations, the National Research Council (NRC) Decadal Survey of Civil Aeronautics, and the Future Aviation Safety Team (FAST) areas of change. Future research direction in the VHM research areas is evidently strong as seen from recent research solicitations from the Naval Air Systems Command (NAVAIR), and VHM-related technologies actively being developed by aviation industry leaders, including GE, Boeing, Airbus, and UTC Aerospace Systems. Given the highly complex VHM systems, modifications can be made in the future so that the Vehicle Systems Safety Technology Project (VSST) technical challenges address inadequate maintenance crew’s trainings and skills, and the certification methods of such systems as recommended by the NTSB, NRC, and FAST areas of change.

15. SUBJECT TERMS
Aviation Safety Program; Commercial Aviation; National Transportation Safety Board; Vehicle Health Management

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER ***(Include area code)***
U	U	U	UU	58	(443) 757-5802